# TEC MEASUREMENTS FOR GPS COMPARISONS AND IONOSPHERIC TOMOGRAPHY

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This report results from a contract tasking University of Wales as follows: The contractor will investigate the validity of the SCORE analysis processes for the determination of GPS TEC, and also the contribution of the protonospheric section of the path of the propagation error budget..

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# TEC MEASUREMENTS FOR GPS COMPARISONS AND IONOSPHERIC TOMOGRAPHY

## Introduction

The project was concerned with support for experimental observations in UK of radio transmissions from both NNSS and GPS satellites that are used to determine electron content along the propagation path through the ionised atmosphere. The ambitious goals specified in the original proposal were four fold:

1. Comparisons of GPS TEC measurements, analysed by the SCORE process, with corresponding values of ionospheric TEC from NNSS observations.
2. Investigation of the protonospheric contribution to the GPS TEC measurements.
3. Production of tomographic images of electron density over UK from NNSS passes.
4. Study of the development of the main trough using the tomographic images.

It can be reported that all of the goals have been achieved within the wider programme of the research of the Radio and Space Physics Group at Aberystwyth. The limited funding available in the present award has been used as planned, to support some of the experimental observations and to facilitate some of the basic analysis of the measurements.

The results obtained in this project have, for the most part, been written up in papers prepared for publication in the open literature. In consequence, the current report takes the form of a series of the papers that describe and discuss the various aspects of the research. These are included in the form of Appendices to the current document.

The first two of the aims outlined above have been achieved in results that have been presented in four papers prepared for publication in Radio Science. These describe respectively, modelling studies on the contribution of protonospheric electrons to GPS TEC, validation of the SCORE process and its application to obtaining GPS TEC measurements in Europe, experimental comparisons of GPS TEC and NNSS TEC differences used to estimate protonospheric electron content, and finally two-station

experimental GPS TEC comparisons that demonstrate the protonospheric influence on GPS systems.

The third aim concerned with the production of radio tomographic images of ionospheric electron density has been achieved with reconstructions being obtained on a routine basis from many satellite passes each day. The observing station at Hawick, supported by the present award, has been included in the chain of five stations spanning the latitude range of UK that are used to record the NNSS TEC measurements used to create the images. These observations have formed the basis for the study of the main ionospheric trough in fulfilment of the fourth aim of the current project and have been used in the development of a model of the trough formulated from tomographic images. The results from these aspects of the work are described in three further papers, prepared and presented at various meetings, that are included as Appendices here.

**List of Appendices**

Appendix A Manuscript of paper on 'The influence of the protonosphere on GPS observations: simulations using the SUPIM model' submitted to Radio Science in September 1998 and accepted for publication in December 1998.

Appendix B Manuscript of paper on 'The effect of the protonosphere on the estimation of GPS TEC: validation using the SUPIM model' submitted to Radio Science in November 1998 and accepted for publication with minor revisions in January 1999.

Appendix C Manuscript of paper on ' The contribution of the protonosphere to GPS total electron content: experimental measurements' submitted to Radio Science in November 1998.

Appendix D Manuscript of paper on 'The protonospheric contribution to GPS TEC:

two-station measurements' submitted to Radio Science in December 1998.

Appendix E Paper entitled 'A new approach to modelling of the main ionospheric trough over Europe using tomographic images' presented at COST251 Workshop, El Arenosillo, Spain, October 1998 and prepared for inclusion in the Conference Proceedings.

Appendix F Paper entitled 'The role of radio tomography in monitoring the near-Earth space environment' presented at European Space Agency Symposium on Space Weather, Noordwijk, Netherlands, November 1998 and prepared for inclusion in the Symposium Proceedings.

Appendix G Paper entitled 'Imaging and modelling of the main ionospheric trough using radio tomography' prepared for presentation at the IEE National Antennas and Propagation Meeting, to be held in York, UK in April 1999.

**Appendix A** Manuscript of paper on 'The influence of the protonosphere on GPS observations: simulations using the SUPIM model' submitted to Radio Science in September 1998 and accepted for publication in December 1998.

The paper reports results from modelling studies carried out to understand the possible effects on GPS systems of electrons in the protonosphere above 1100km altitude. The code for the Sheffield University Plasmasphere Ionosphere Model (SUPIM) was made available to the Radio and Space Physics Group at Aberystwyth by G. J. Bailey of the University of Sheffield. Estimates are presented of the protonospheric contribution to the total electron content relevant to GPS observations in both Europe and North America for both minimum and maximum solar activity. The key influence of GPS ray path geometry with respect to the plasmaspheric flux tubes is demonstrated.

# The influence of the protonosphere on GPS observations: Simulations using the SUPIM model

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**Abstract.** The accuracy of the Global Positioning System (GPS) satellite navigation system can be degraded by propagation effects on ray paths through the ionized atmosphere. The bulk of the plasma resides in the *F* layer, and models of total electron content have been developed to compensate for the effects of this ionization. However, use of the GPS system involves long ray paths through the tenuous hydrogen-based plasma of the protonosphere, and little is known about the electron content in this region. In the present study, the Sheffield University plasmasphere ionosphere model (SUPIM) has been used to determine the electron content on the protonospheric section of GPS ray paths. Results are presented for stations at midlatitudes in the European and American sectors at both extremes of the solar cycle. The results are discussed in terms of the geometry of the flux tubes and the known behavior of the plasma.

## 1. Introduction

The hydrogen-dominated plasma in flux tubes in the high plasmasphere or protonosphere is not well understood, although the effects of the free electrons on signals traversing the region may be of significance to the reliable operation of radio systems. The present paper is the first in a series that report results from both modeling and experimental studies of the electron content on ray paths through the protonosphere. The investigations are of importance to schemes for mitigation against propagation effects on some applications of the satellite navigation Global Positioning System (GPS).

Satellites in the GPS system are in orbits at an altitude of about 20,200 km, inclined at 55° to the equatorial plane. Reception of signals from four satellites enables the position of the observer to be estimated. Two frequencies are transmitted so that by using an appropriate receiver, allowance can be made for the effects of the ionized atmosphere on the signal propagation and hence on the accuracy of the positional estimate. However, many navigation uses of GPS rely on inexpensive single-frequency receivers, with compensation for the propagation environment being made through use of a model of ionospheric electron content, like that of *Klobuchar* [1987] broadcast by the GPS satellites. Models of electron content, of various degrees of complexity, have been developed over several decades to correct for ionospheric propagation effects. Most of the models are essentially empirical and are based on ionospheric measurements of maximum plasma frequency or of the total electron content itself. Estimates of the latter parameter have been made over many years using radio transmissions from satellites. Measurements of this kind are dominated essentially by the plasma in the ionospheric

$F_2$ layer so that little account is taken in the GPS correction models of the contribution of the electrons on the long ray paths through the protonosphere. The present work aims to assess the significance to GPS users of the electron content in the hydrogen plasma of the protonospheric flux tubes.

## 2. Background

Ionization moves between the topside ionosphere and the protonosphere. During daytime the solar-produced oxygen plasma of the ionospheric $F$ region diffuses up the magnetic field. The oxygen ions charge exchange with neutral hydrogen to give a hydrogen-dominated plasma above some transition altitude. The hydrogen ions and electrons drift upward along the field lines to populate the closed flux tubes of the plasmasphere. After ionospheric sunset, the hydrogen plasma in the protonosphere can return to lower altitudes, where it charge exchanges to form an oxygen plasma that helps to maintain the nighttime $F$ region.

It is useful to treat the midlatitude plasmasphere as consisting of winter and summer ionospheres, linked by a common protonosphere along the field lines joining the conjugate hemispheres (Figure 1). The ionospheres act as sources of plasma, and the protonosphere acts as a reservoir [*Bailey et al.*, 1978]. There is an exchange of plasma on a diurnal basis, with the winter ionosphere benefiting from plasma produced in the conjugate summer ionosphere.

The variation of the volume of the flux tube with the latitude of its ionospheric footprint greatly influences the behavior of the electron density in both the protonosphere and the underlying ionosphere. The shortest tubes with bases at low magnetic latitude are in approximate equilibrium with the underlying ionosphere and have little effect on it in terms of electron content. As the latitude of the ionospheric footprint increases, so does the volume of the tube, so that a longer period of dayside filling is required before a tube is in equilibrium with the underlying ionosphere. In the outermost regions of the protonosphere the volume is so great that the upward flux during daytime cannot produce an equilibrium pressure profile and there is partial depletion at night before filling is resumed the next day [*Carpenter and Park*, 1973].

The outer boundary of the plasmasphere, termed the plasmapause, is essentially the limit for magnetic flux tubes that corotate with the Earth. The position of the plasmapause varies with local time, a bulge in the dusk sector giving rise to the pear-like shape of a plasmaspheric section in the equatorial plane [*Chappell*, 1972]. This bulge results from the opposition at this local time of the corotation flow near to the Earth and the sunward convection of the magnetosphere driven by the solar wind. During geomagnetic storms the sunward convection is

enhanced, causing a contraction of the plasmapause and rapid depletion of the protonospheric flux tubes around dusk on the first day of the storm. The replenishment of the protonospheric plasma from the underlying ionosphere then occurs for a period of many days after the storm. Indeed, for the large-volume flux tubes mapping to subauroral latitudes, the filling time is generally greater than the recurrence time between storms, so that the plasmasphere can be thought of as generally in a state of partial replenishment [*Carpenter and Park*, 1973; *Kersley et al.*, 1978; *Kersley and Klobuchar*, 1980].

The essential form of the plasmasphere was inferred from observations of VLF whistlers several decades ago. However, there have been few experimental measurements of the electron content on ray paths through the protonosphere. The ATS 6 satellite radio beacon experiment in the mid-1970s provided a unique opportunity for such work. The difference between the total electron content measured by the group delay technique and that from Faraday rotation gave an indication of the content on the protonospheric section of the ray path to the geostationary satellite [*Kersley and Klobuchar*, 1978] that was at times a significant fraction of the total [*Hargreaves*, 1998]. Protonospheric content estimates from differences between GPS and Faraday rotation total electron content (TEC) measurements were presented by *Doherty et al.* [1992]. Early modeling work relating to the ATS 6 experiment was reported by *Sethia et al.* [1983] and an empirical model of the plasmasphere has been presented by *Gallagher et al.* [1988].

The present project aims to remedy the gap in knowledge about the protonosphere in two ways. First, the Sheffield University plasmasphere ionosphere model (SUPIM), a physical model, has been used to study the expected behavior of the electron content on the protonospheric sections of the ray paths from GPS satellites under a variety of conditions. Second, the modeling work has been complemented by actual experimental measurements made using GPS observations at appropriate locations and also aided by observations of Navy Ionospheric Monitoring Satellites (NIMS) in low Earth orbit. The current paper is concerned with the modeling aspects of the study.

## 3. The SUPIM Model

The modeled values have been determined from SUPIM, the Sheffield University plasmasphere ionosphere model [*Bailey and Sellek*, 1990; *Bailey et al.*, 1993; *Bailey and Balan*, 1996]. In SUPIM , coupled time-dependent equations of continuity, momentum, and energy balance are solved by an implicit finite difference scheme along closed magnetic field lines between base altitudes of about 120 km in conjugate hemispheres in order to give values for the concentrations, field-aligned fluxes, and temperatures

of the $O^+$, $H^+$, $He^+$, $N_2^+$, $O_2^+$, and $NO^+$ ions, and the electrons, at a discrete set of points along the field lines. For the present study, the geomagnetic field is represented by a tilted dipole that reproduces in a realistic way the displacement of the geomagnetic and geographic equators and the magnetic declination angle. The concentrations and the temperatures of the neutral gases are obtained from the MSIS86 thermospheric model [*Hedin*, 1987], the neutral wind velocities are obtained from the HWM90 neutral wind model [*Hedin et al.*,1991] and the solar EUV fluxes are obtained from the EUVAC solar EUV flux model [*Richards et al.*, 1994]. The remaining model inputs, for example, the photoionization and photoabsorbtion cross sections, chemical reaction rates, heating (including photoionization heating) and cooling rates, and collision frequencies, are described by *Bailey at al.* [1993] and *Bailey and Balan* [1996].

## 4. The Method

The protonospheric flux tubes are replenished by a net upward flux of plasma from the underlying ionosphere. For the present work, the simulated refilling time has been taken to be 16 days. In practice, the recurrence time between the magnetic storms that cause contraction of the plasmapause and depletion of the protonosphere averages less than 2 weeks. In consequence, the conditions modeled here correspond to as full a plasmasphere as would likely be encountered in reality. The SUPIM model was run with a simulated buildup time of 16 days to yield the electron densities in flux tubes up to a plasmapause that was taken to be at L=4. It can be noted that the assumption of a fixed plasmapause with no protonospheric plasma in the higher L-shell flux tubes represents a limitation to the present study, but it does not invalidate the conclusions. From these field-aligned electron densities, the densities along the ray paths through the plasma continuum of the protonosphere and ionosphere from GPS satellites to ground stations were then calculated at 25-km intervals. A numerical integration of these electron densities gave the electron contents. The bulk of the electrons are in the ionospheric section of the path, in the $F_2$ layer at altitudes of a few hundred kilometers. For the present study the upper limit of the ionospheric plasma has been taken to be at 1100 km, well above the layer peak. The choice of this limit is somewhat arbitrary and is not critical to the results. The height of 1100 km was chosen since this is the altitude of the NIMS satellites that were used to determine the ionospheric electron content in the experimental part of the current study that will be described in a forthcoming paper.

## 5. Results

The first results are concerned with simulations using SUPIM of observations in the European sector under solar minimum conditions with a 10.7-cm solar

flux of 75 x $10^{-22}$ W $m^{-2}$ $Hz^{-1}$. Estimates of electron content were obtained for assumed vertical ray paths with the integration being carried out both to GPS (20,200 km) and NIMS (1100 km) altitudes, the difference between the values being taken as a measure of the protonospheric content. Sample results are presented in Figure 2 in the form of diurnal curves. The geographic latitudes of the stations have been chosen to range from 40°N to 55°N. Three sets of curves are shown, representative of conditions at equinox and both solstices. The diurnal plots of Figures 2a, 2b, and 2c show that the protonospheric content on vertical ray paths increases with decreasing latitude. It can be seen that above a station at 40°N, the protonospheric section of the vertical ray path has a content of less than 3 $\times$ $10^{16}$ $m^{-2}$, that is, 3 total electron content units (3 TECU), while at 55°N the value is always below 1 TECU. There is little evidence from the plots of any significant diurnal or seasonal change in the electron content on these ray paths through the protonosphere. The sampling interval was 30 min, and the small-scale structure found in the plots is of no significance.

Consideration of Figure 1 shows that in the European sector the tilt of the magnetic dipole results in flux tubes outside the plasmapause at L=4 being encountered on a vertical ray path at a relatively low altitude. In consequence, the low protonospheric electron content with little diurnal change found in the model simulations above is in keeping with expectations from considerations of the flux-tube geometry. It is also apparent from Figure 1 that protonospheric content on vertical ray paths would be expected to increase with decreasing latitude of the observing station. The magnitude of the effect on positioning can be assessed when it is appreciated that 6.15 TECU corresponds to an error of 1 m at the L1 GPS frequency. However, although the absolute magnitude of the protonospheric effect may be small for the conditions shown here, nevertheless under certain circumstances it can represent a significant fraction of the total electron content along the entire ray path. The results of Figures 2a, 2b and 2c are replotted in Figures 2d, 2e, and 2f but are now expressed as percentages. It can be seen that during the night in winter the protonospheric contribution can exceed 50% at the lower latitudes and be more than 30% at the highest latitude considered here. The daytime percentages are generally in the range 10-30% in winter, with a slightly smaller upper limit for the lowest latitudes at other seasons.

In practice, GPS satellites are viewed from a given station at many elevation angles, so that the slant electron content along the ray paths through the protonosphere is usually of greater relevance than that found vertically above the receiver location. Figure 3 shows the slant protonospheric electron contents estimated from the SUPIM model for a variety of representative conditions at solar minimum. The results

are given both in absolute and percentage terms, with March being chosen as the representative month and plots shown for both midday and midnight. The graphs give the protonospheric content for ground stations in the latitudinal range 40°N-55°N and ray paths in the meridian. The elevation angles of the rays chosen range from 10°, due south of the station, to 130°, that is, 50° above the horizon to the north. At midday, the protonospheric ray paths at the lowest angle to the south show contents of almost 5 TECU, representing some 20% of the total electron content, the ionosphere contributing the balance of 80%. For 50° elevation the absolute protonospheric content varies with latitude, yielding values between 3 and 4 TECU, though the percentage is now about 30%. For the paths at 50° to the north, the protonosphere contributes less than 1 TECU, or 10%, even at 40°N latitude.

The plots for midnight differ from those for daytime in that the absolute values on the lowest elevation ray paths to the south now range between 3 and 4 TECU and there is evidence for a small diurnal interchange, particularly for observations at the lowest latitudes where the ray paths are intersecting the short inner flux tubes. The percentage contribution here is some 50%, and even at high elevations and the higher latitudes considered the protonospheric content may amount to 30% at night.

The results discussed to date have been for solar minimum conditions. However, during an increasing phase of the solar cycle it is appropriate to consider the possible effect of protonospheric contents on ray paths to GPS satellites at solar maximum. For the purposes of the present study a large solar flux of $250 \times 10^{-22}$ W $m^{-2}$ $Hz^{-1}$ has been chosen as representative of the peak of a solar cycle. The work has been repeated using SUPIM to estimate the protonospheric electron content at solar maximum, and a set of plots is shown in Figure 4, for conditions corresponding exactly to those of the solar minimum results of Figure 3. In comparison with the plots for solar minimum, Figure 4 shows slant protonospheric contents that are typically doubled, though for low elevation at the lowest latitude the increase is even larger, with the absolute magnitude reaching 14 TECU. However, the percentage contribution from the protonosphere is now generally only about 10% at midday and between 10% and 15% at midnight.

The investigations presented so far have concentrated on studies appropriate to European longitudes where the tilt of the geomagnetic dipole results in the magnetic latitude of a station being greater than its geographic equivalent. Figure 1 illustrates that for stations in the American sector the situation is reversed, with the geographic latitude exceeding that of the magnetic field. In consequence, the intersection geometries of GPS ray paths with the magnetic flux tubes are different for stations in North

America when compared with those in Europe. To investigate this difference, studies have been carried out using the SUPIM model to estimate the electron content on protonospheric ray paths from GPS satellites to stations along the 90° west longitude.

As an example of the differences found between the European and American sectors sample plots are presented in Figure 5 for stations at 40°N during the March equinox at both extremes of the solar cycle. The diurnal variation of vertical total electron content is shown in each panel, estimated to both GPS and NIMS altitude. The difference between the curves gives the contribution on the protonospheric section of the ray path. The change in scale between solar minimum and maximum must be noted. It can be seen that while the protonosphere may contribute 2 TECU at solar minimum at European longitudes, the corresponding value for a station at the same latitude in the American sector is only about 0.5 TECU. While the protonospheric content at the bottom of the solar cycle may be 50% of the total at night at 0° longitude, the corresponding fraction is only some 25% at 90°W. The lesser importance of the protonospheric content in the American sector is what would be expected from considerations of the flux tubes and the dipole tilt. Figure 1 shows that higher L shells, with consequent lower electron densities, are encountered at lower altitudes along the American sector ray path than over Europe. The model results for solar maximum also shown in Figure 5 confirm the greater importance of the protonosphere to observations at European than American midlatitudes. However, in percentage terms the protonospheric contribution is of lesser importance than at solar minimum in both sectors.

## 6. Conclusions

The SUPIM model has been used to estimate the contribution of the electron content arising from the protonosphere along ray paths from GPS satellites. Results have been presented simulating the effects for observing stations at midlatitudes in Europe and America at both solar maximum and solar minimum. The values provide guidance for some users of the GPS system concerning possible additional effects arising from plasma well above the ionospheric *F* layer. For stations at midlatitudes in the northern hemisphere the protonospheric electron content is of greatest significance to ray paths to the south, and it shows variations that are in broad agreement with those anticipated from considerations of flux-tube geometry and the known behavior of the plasma. For European observations at solar minimum the contribution from the protonosphere is generally only a few TEC units in absolute terms. However, at night, particularly in winter, it may constitute 50% or more of the total electron content along the GPS ray path. At solar maximum, the protonospheric contents are typically doubled in absolute magnitude but are greatly reduced

in percentage terms. The modeling work also indicates that because of the dipole tilt of the Earth's magnetic field, the protonosphere is of lesser significance to GPS observations in America than in Europe.

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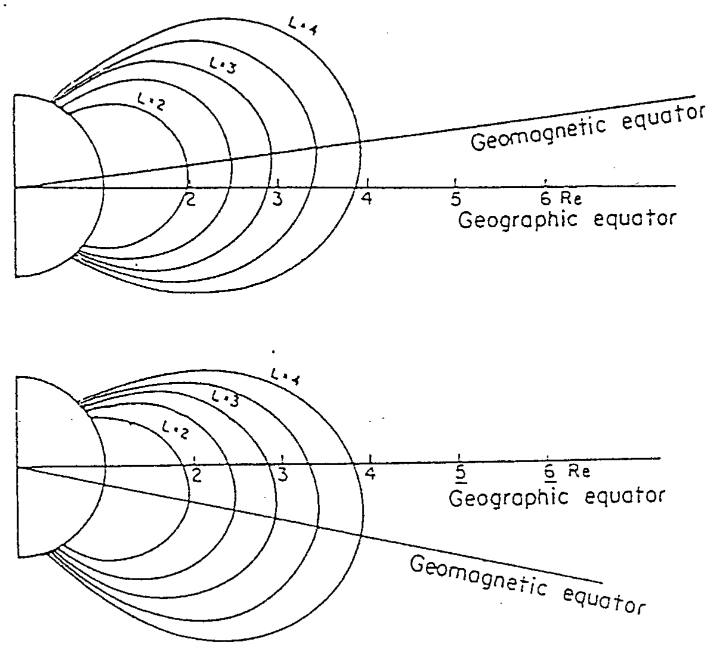


**Figure 1.** Protonospheric flux-tube configurations for (top) European and (bottom) American sector longitudes.

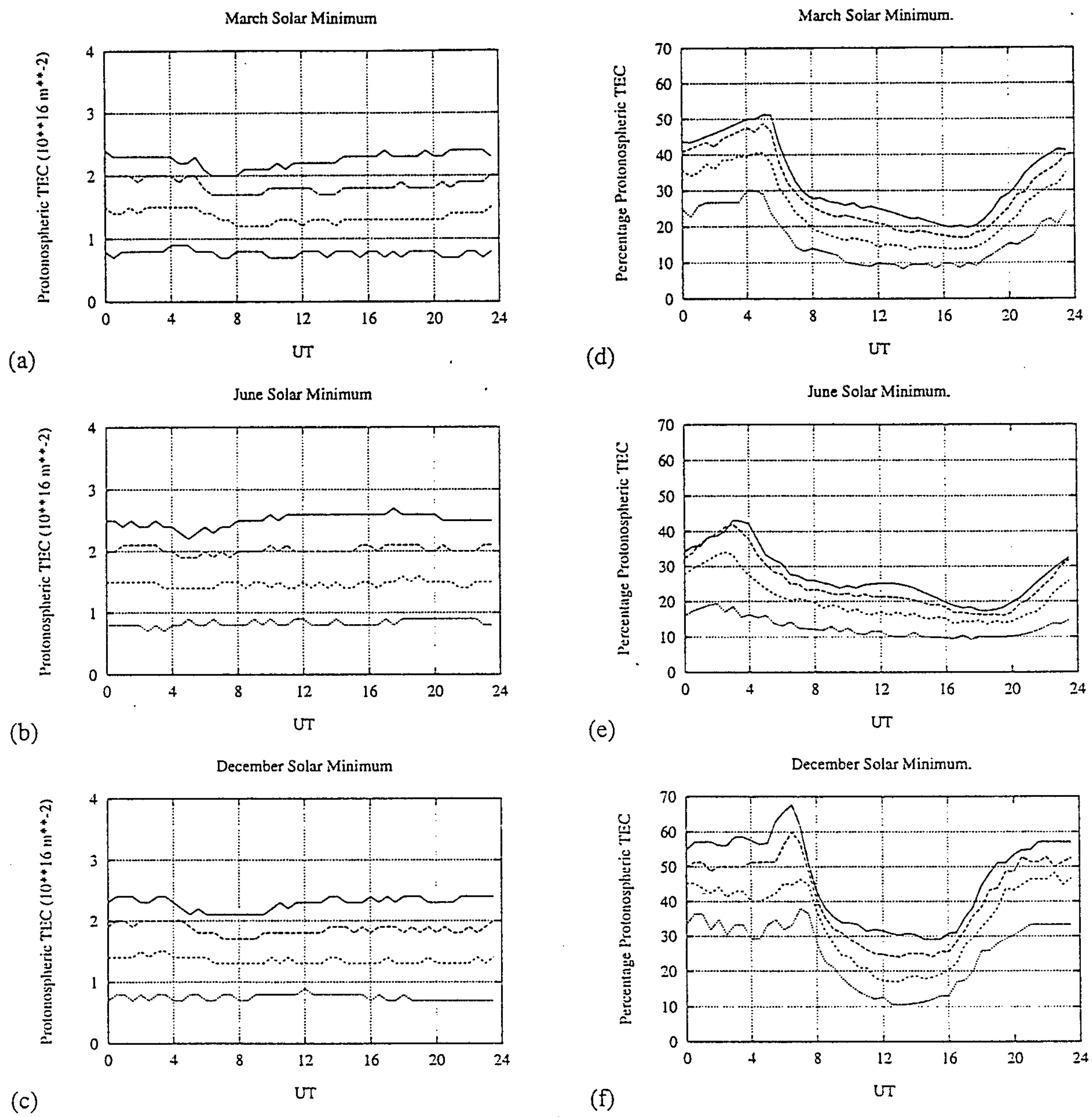


**Figure 2.** (left) Absolute and (right) percentage diurnal variations of the protonospheric electron content on vertical ray paths, for observations at European longitudes at solar minimum for the three months labeled. Station latitudes are designated as follows: solid lines, 40°N; long-dashed lines, 45°N; short-dashed lines, 50°N; and dotted lines, 55°N.

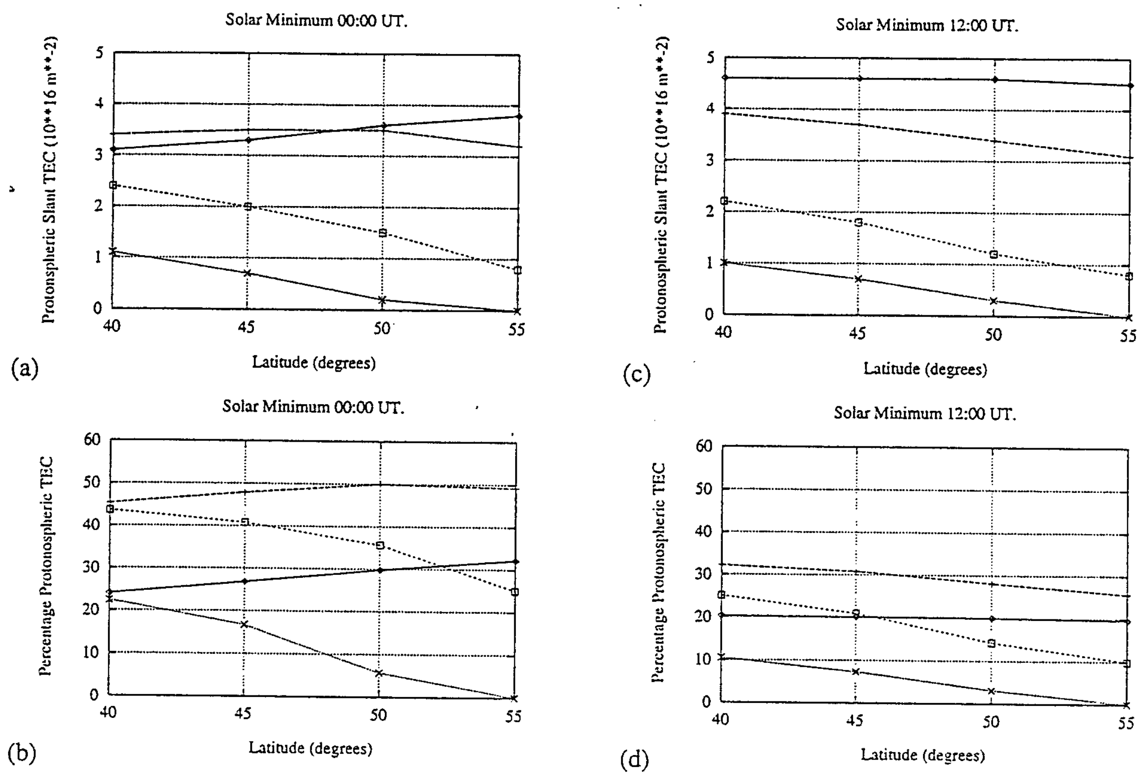


**Figure 3.** (top) Absolute and (bottom) percentage protonospheric electron contents on slant ray paths for European observing stations in the latitude range 40°N - 55°N at solar minimum. Figures 3a and 3b refer to conditions at 0000 UT, and Figures 3c and 3d correspond to 1200 UT. Ray path elevation angles from the southern horizon are designated as follows: solid lines, 10°; long-dashed lines, 50°; short-dashed lines, 90° and dotted lines, 130°.

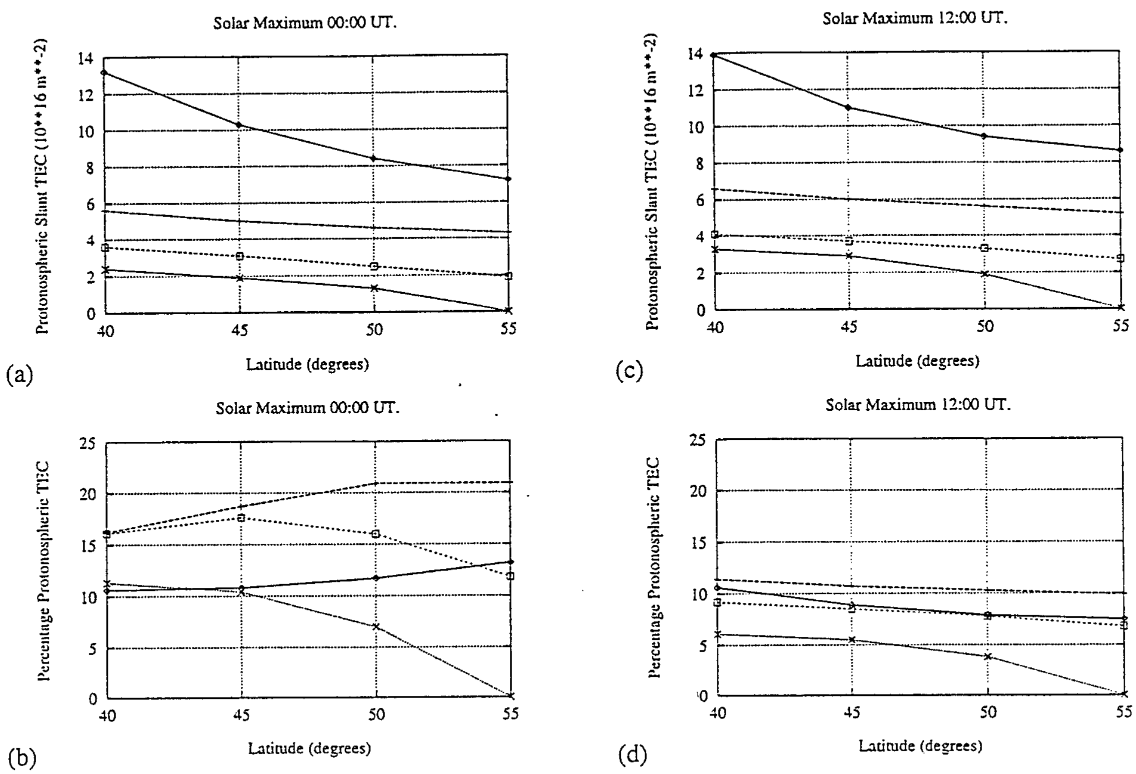


**Figure 4.** Same as Figure 3, but for solar maximum.

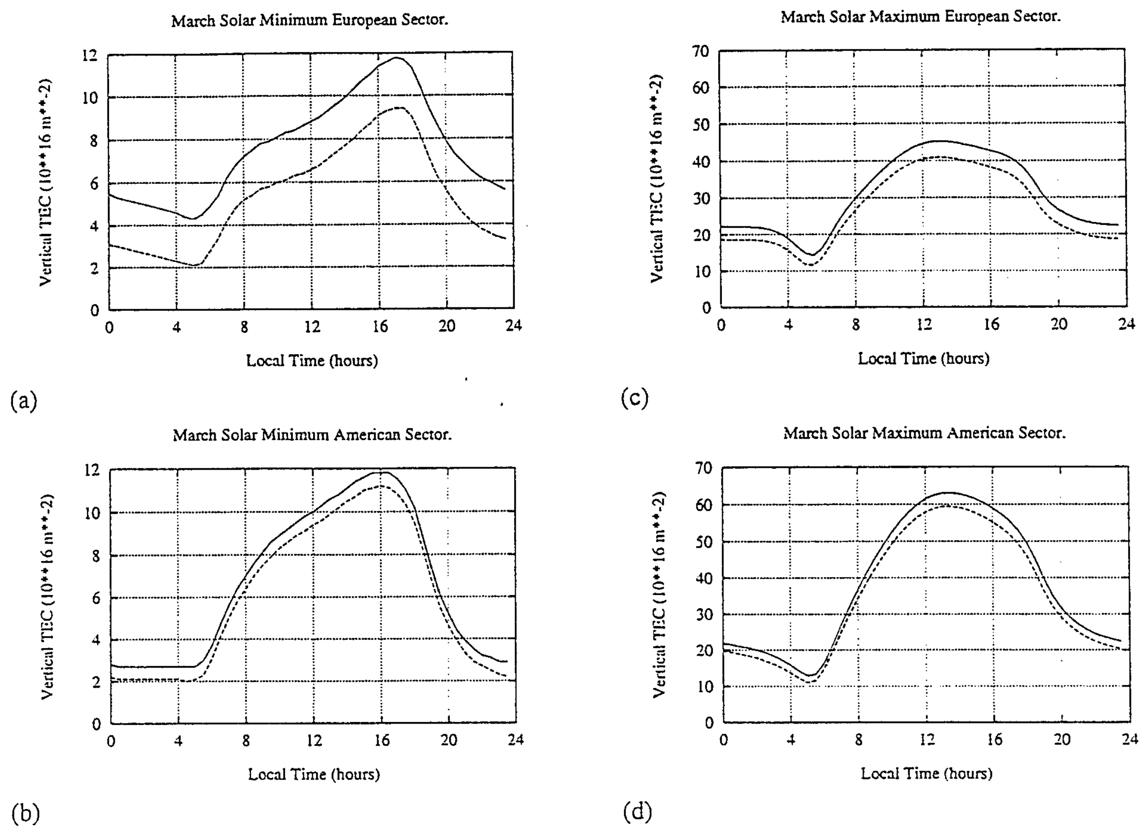


**Figure 5.** Diurnal variations of equivalent vertical electron content integrated to Navy Ionospheric Monitoring Satellite altitude of 1100 km (solid lines) and to Global Positioning System altitude of 20,200 km (dashed lines) for March. The top panels relate to observations at a station latitude of 40°N in the European sector, and the bottom panels correspond to a station at a similar latitude in America (90°W). Figures 5a and 5b refer to solar minimum, and Figures 5c and 5d are for solar maximum.

**Appendix B** Manuscript of paper on 'The effect of the protonosphere on the estimation of GPS TEC: validation using the SUPIM model' submitted to Radio Science in November 1998.

The paper reports on a study undertaken to validate the Self Calibration Of pseudo-Range Errors (SCORE) procedure used to obtain total electron content from GPS observations. The SCORE process was developed by G J. Bishop and A. J. Mazzella at the Air Force Research Laboratory who made the code available to the Aberystwyth group for the current project. The verification was carried out using simulated TEC observations derived from the Sheffield University Plasmasphere Ionosphere Model (SUPIM) made available by G. J. Bailey.

The study demonstrated that the basic SCORE process overestimated the TEC by some 2 TEC units when used for GPS observations at Aberystwyth at solar minimum, with corresponding underestimation of the unknown satellite-plus-receiver biases. The offset arises from the asymmetric geometry of the protonospheric flux tubes with respect to the observing location. It is shown that a simple modification to the basic SCORE process to allow for the protonospheric asymmetry yields TEC values accurate to better than 1 TEC unit.

# The effect of the protonosphere on the estimation of GPS TEC: validation using the SUPIM model

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*Abstract*

*Simulated observations of electron content along ray paths from GPS satellites have been used to validate the estimation of TEC using GPS measurements. The Sheffield University Plasmasphere Ionosphere Model (SUPIM) has been used to create electron densities that were integrated along ray paths from actual configurations of the GPS constellation. The resultant slant electron contents were then used as inputs to validate the Self Calibration Of pseudo-Range Errors (SCORE) process for the determination of TEC from GPS observations. It is shown that, if the plasma can be taken to be concentrated in the ionosphere below 1100km, then the SCORE procedure determines the TEC to a high degree of accuracy. When the contribution of the electrons in the protonosphere above 1100km is included, the analysis results in TEC estimates that are high by some 2 TECU for conditions appropriate to European mid-latitudes at solar minimum. However, if a restriction is placed in the analysis on use of observations equatorwards of the station, then allowance can be made for the effect of the protonosphere. It is shown that, with appropriate selection of the boundary for the observations, TEC can be estimated by SCORE to better than 1 TECU for the conditions of the simulation. Sample results are included from actual experimental observations using GPS to demonstrate the effect of compensation for the protonospheric plasma.*

## Introduction

Signals from navigation satellites in the Global Positioning System (GPS) are used to determine total electron content (TEC), a parameter needed in corrections for propagation effects of the ionised atmosphere in some radio system applications. Indeed, the GPS

system is increasingly becoming the main source for monitoring and mapping TEC on local, regional and global scales. Ground-based receivers monitor signals from several GPS satellites simultaneously on ray paths covering a wide range of azimuths and elevations. In principle, the slant total electron content along a ray path can be determined from the received signals, though the measurements are offset by unknown biases arising from phase delays in both the satellite transmitter and the ground-based receiver.

Analysis techniques have been developed that use the observations from many satellites with random ray path geometries to yield absolute values of equivalent vertical total electron content. Various attempts have been made to verify such techniques using independent measurements, but the difficulties in obtaining exact correspondence in space and time for the observations has limited the accuracy of the comparisons (Bishop et al., 1997a; Mannucci et al., 1998). The present paper reports, for the first time, a new approach to validation. In addition, it highlights the necessity to make allowance in the analysis procedure for the effects of electrons on the high section of the ray path through the protonosphere.

Simulated measurements of total electron content along GPS ray paths have been generated using the Sheffield University Plasmasphere Ionosphere Model (SUPIM). The simulated observations were then adjusted with arbitrary offsets to represent the unknown biases. The Self-Calibration of pseudo-Range Errors (SCORE) technique (Bishop et al., 1996) was then used to process the measurements to recover both the arbitrary offsets and the equivalent vertical total electron content in a manner similar to that used for actual experimental observations.. It is demonstrated that, with appropriate modification to compensate for the effects of electrons in the high protonosphere, the SCORE process can be used to determine total electron content to a high degree of accuracy.

There are other techniques for extracting GPS TEC to which the validation process could be applied. For example, Ciraolo and Spalla (1997) employed a Kalman filter process to data from 19 stations, using one as a reference. Other approaches include Gardner (1995) who applied a discrete inverse theory technique, and Sardon and Zarraoa (1997) who used a process combining least squares, Kalman filtering and an assumed linear latitudinal TEC variation.

## The SCORE process

The SCORE concept is to use a self-consistency constraint on the receiver's own measurements of ionospheric delay to derive the *sum of the receiver system and satellite pseudorange error* for each satellite. The self-consistency concept is illustrated by considering a "conjunction" occurring between two satellites, that is an event where both satellites arrive at the same moment at a point where their observed paths cross. In such an event the same ionospheric pseudorange error (TEC value) should be seen on each satellite. SCORE works by requiring maximum agreement in ionospheric measurements at local time at the penetration point (IPP LT) - latitude "conjunctions", within a defined correlation region. SCORE uses 24 hours of data from a single receiver. It operates

without using any test signal, assuming any model ionosphere, or applying data from an observing network. Used in this fashion, the SCORE process assumes that biases remain constant over the 24 hours, although shorter intervals may be used.

In application of the SCORE process a restriction arises from the slant factor formula used to convert slant TEC measurements into equivalent vertical TEC. This formula has been derived on the basis of an infinitesimally thin ionosphere, which is not an appropriate assumption. This error decreases at higher elevation angles, so the current parameters utilized for the SCORE algorithm include a threshold elevation of 35 degrees for satellite track segments which will be correlated. A beneficial secondary effect of this assignment is that the correlated segments cannot then differ in real-time occurrence by more than 32 minutes, reducing the possibility of intrinsic ionospheric variations adversely affecting the correlations. Within the above constraints, the correlation region for each satellite pair is Gaussian weighted with a wide outer cutoff, assuring pairing for all satellites and emphasis on the best "conjunctions". Absolute TEC data (differential pseudorange) are initially fitted to differential phase (relative TEC) data to suppress multipath, a process often referred to as "phase-averaging". With this preparation, the biases resulting from the SCORE process give the summed instrumental pseudorange errors for each satellite, suppressing most multipath effects.

**The SUPIM model**

The modelled values have been determined from SUPIM, the Sheffield University Plasmasphere Ionosphere Model (Bailey and Sellek, 1990; Bailey et al., 1993; Bailey and Balan, 1996). In SUPIM , coupled time-dependent equations of continuity, momentum and energy balance are solved by an implicit finite-difference scheme along closed magnetic field lines between base altitudes of about 120km in conjugate hemispheres to give values for the concentrations, field-aligned fluxes and temperatures of the $O^+$, $H^+$, $He^+$, $N_2^+$, $O_2^+$ and $NO^+$ ions, and the electrons, at a discrete set of points along the field lines. For the present study, the geomagnetic field is represented by a tilted dipole that reproduces in a realistic way the displacement of the geomagnetic and geographic equators and the magnetic declination angle. The concentrations and temperatures of the neutral gases are obtained from the MSIS86 thermospheric model (Hedin, 1987), the neutral wind velocities from the HWM90 neutral wind model (Hedin et al., 1991) and the solar EUV fluxes from the EUVAC solar EUV flux model (Richards et al., 1994a, 1994b). The remaining model inputs, for example, the photoionisation and photoabsorption cross sections, chemical reaction rates, heating (including photoelectron heating) and cooling rates and collision frequencies, are described in Bailey at al. (1993) and Bailey and Balan (1996).

**Method**

The SUPIM model has been used to estimate the electron content along simulated ray paths from GPS satellites to a ground station at Aberystwyth (52.4°N, 4.1°W). Further information about use of SUPIM to simulate GPS observations can be found in a

companion paper (Lunt et al., 1998). The positions and motions of the satellites were chosen to correspond to those of actual configurations of the GPS constellation on particular days. Five days were used, spread over a period of about a year in 1997/8. The electron content was calculated for all ray paths above an elevation of 35 degrees. The electron contents corresponding to observations from each satellite were then adjusted by the addition of an arbitrary offset to simulate the effect of the unknown satellite plus receiver bias of actual measurements. The offsets, which differed for each space vehicle, lay within the range 12.5 to 27.5 total electron content units (1 TECU ≡ $10^{16}$ electrons $m^{-2}$), again being chosen to simulate the combined unknowns of the satellite plus receiver biases encountered in practice. The resultant relative electron contents for all ray paths to all satellites above 35 degrees elevation, estimated at a data interval of 1 minute, were input to the SCORE process, in a procedure identical to that used for actual experimental measurements.

**Results**

In an initial validation of the SCORE analysis procedure the slant electron contents were estimated from the SUPIM model along the ionospheric ray paths up to a height of 1100km. This upper limit was chosen because the bulk of the electrons are in the atomic oxygen based plasma of the ionospheric F-layer well below this altitude. Furthermore, 1100km is the orbital altitude of satellites in the Navy Ionospheric Monitoring System (NIMS) and total electron contents determined from NIMS transmissions have been used in the experimental measurements programme of the present study that is described in a later companion paper. The results from the simulation in which only ionisation below 1100km was considered, are presented in Figure 1. The figure shows the equivalent vertical total electron content output from SCORE for simulated observations corresponding to selected days in December, March and June, all at solar minimum. The plot is in the form of the diurnal variation of equivalent vertical TEC, with the graph made up from segments corresponding to ray paths from GPS satellites crossing the ionosphere at a height of 350 km within a one degree latitude band centred on the ground station. The time corresponds to the local time at this ionospheric penetration point (IPP). The solid line represents the diurnal variation of the total electron content in the vertical above the station obtained from the SUPIM model, with integration of the electron density to 1100km altitude. It is clear from Figure 1 that the TEC output from SCORE replicates well the input from SUPIM. The agreement in the equivalent vertical TEC is much better than 0.5 TECU at all times and seasons, with small discrepancies being associated in the main with longitudinal gradients in the ionisation near the extremes of the diurnal plot in June. Similar results were obtained for all five configurations of the GPS satellite constellation used in the study. It can be concluded that the SCORE process for the recovery of the equivalent vertical TEC from slant observations along random ray paths yields very accurate mid-latitude results when the ionisation is concentrated below the chosen altitude of 1100km.

In experimental observations using actual GPS satellites, the ray paths encounter electrons not only in the ionospheric F-layer but also in the hydrogen-dominated plasma of the

protonosphere between 1100 km and the GPS altitude of 20200 km. A study using the SUPIM model of the potential influence of protonospheric electrons on GPS ray paths has been described by Lunt et al. (1998). It was concluded that, for observations at European mid-latitudes at solar minimum, the electrons above 1100km only contributed a few TECU to the total electron content. However, though the absolute magnitude of the protonospheric contribution is small, it could amount to more than 50% of the total, especially during winter nighttime. It is thus important to assess the performance of GPS analysis techniques like SCORE in estimating the TEC in circumstances when the protonospheric effect could be significant.

The study was repeated, using as input to SCORE the slant electron contents obtained from SUPIM with integration of the electron densities up to the GPS height of 20200km. The results are presented in Figure 2 for the solar minimum days and the GPS satellite configuration corresponding exactly to the conditions used for Figure 1. It is clear that while the SCORE output replicates the general form of the diurnal variation of the input, the magnitudes of the TEC results are generally too high by some 2 TECU. In addition, the temporal variation on winter and spring nights shows poor agreement. For example, in December an earlier and larger enhancement in TEC would be inferred from the SCORE output than was actually present in the SUPIM input. Similar discrepancies were found in all of the simulations for other months and satellite configurations at solar minimum, with the SCORE process generally yielding equivalent vertical TECs larger by about 2 TECU than those generated by the model.

The discrepancy between the input and the output shown in Figure 2 arises because the estimates of the satellite plus receiver biases made as part of SCORE minimisation are, in general, too low. This can been seen from Table 1, which lists the arbitrary bias assigned to the simulated observations for each space vehicle, together with the corresponding estimate of that bias obtained from SCORE for the conditions of Figure 2. It is clear that the output estimates are generally low, by an average of 2.1 TECU, in agreement with the high values of equivalent vertical TEC shown in Figure 2. By contrast, the bias estimates for the 'ionosphere only' study corresponding to Figure 1 show an average discrepancy from the known input of less than 0.1 TECU. Thus, while the SCORE technique can recover the satellite biases and the equivalent vertical TEC to a high accuracy when the plasma is concentrated in the ionosphere below 1100 km, when account is taken of electrons on the long ray paths through the protonosphere above 1100 km, then the retrieval procedure used in the current study yields values of satellite biases and hence TECs that are in error by typically 2 TECU. It must be stressed that the present simulation has been concerned with conditions applicable to European mid-latitudes at solar minimum, where the contribution to the GPS total electron content arising from the protonosphere can be of greater significance than for other locations and solar activities (Lunt et al. 1998).

Comparisons of Figures 1 and 2 shows that for the conditions of the present simulation, European observations at solar minimum, the SCORE process is inclined to produce satellite plus receiver bias estimates that are too low, and consequently TEC values that

are high, because of the effect of protonospheric electrons. To understand and compensate for the effects of the protonospheric ray paths it is necessary to appreciate both the geometry and dynamics of the plasmaspheric flux tubes. A full discussion of the protonosphere has been given in the companion paper (Lunt et al., 1998). The key point of note for the present study is that because of the magnetic field geometry (Figure 3) GPS ray paths with decreasing elevations to the south of a European mid-latitude station encounter an increasing number of protonospheric electrons. By contrast, ray paths to the north cross the higher L shell flux tubes containing fewer electrons at lower altitude so that their total protonospheric electron contents are small. An additional factor to be borne in mind is that the 55° inclination of the GPS satellite orbits can limit the possible coverage of ray paths to the north. It is the protonospheric contribution, which exhibits meridional asymmetry as seen from a mid-latitude station, that is responsible for the breakdown of the SCORE process evident in Figure 2. It should be remembered that the results in Figure 2 were obtained using simulated total electron contents for all ray paths from a GPS constellation for which the elevation angle at the ground exceeded 35°.

As an approach to compensating for the increased protonospheric electron content on ray paths to the south, it was decided to limit the use of data from these lower elevation angle ray paths in the retrieval process. This was done by setting a lower latitude boundary for the ionospheric penetration points at 350 km of the ray paths for the observations used as input to SCORE. In this way, the lower elevation ray paths to the south containing the greatest number of protonospheric electrons were excluded from the analysis. A similar application of protonospheric asymmetry has lead to a new technique for measuring protonospheric TEC (Bishop et al., 1997b). Of course, appropriate selection must be made of this lower latitude boundary. To facilitate this choice, a study was carried out to investigate the dependence on the lower latitude cut-off of the error in the output electron content when compared to the known input from the model. The study used a data interval of 15 minutes and involved simulated observations for 5 different configurations of GPS satellites for each of the days chosen. The overhead TEC obtained from SCORE was differenced from the corresponding vertical TEC generated by SUPIM. The average of these differences, over the 24-hour period and all of the satellite constellations, was then used as an indicator of the error in the SCORE process. This average is plotted in Figure 4 as a function of the low latitude cut-off, for a limited range of this parameter. It can be seen that the error is sensitive to the selection of the lower latitude boundary and that for observations at Aberystwyth (52.42°N) a lower latitude cut-off of 51.65°N, that is 0.75° south of the station, is the appropriate choice to give zero average error in the TEC estimates.

The simulated GPS observations were reprocessed, with the exclusion of ray paths whose ionospheric penetration point latitude was less than 51.65°N. The resultant diurnal plots of equivalent vertical TEC are shown in Figure 5, for the same conditions as in Figures 1 and 2. It is clear that the overall forms of the diurnal curves made from the individual segments now match the vertical TEC from the model. The scatter in the difference between output and input is now, in general, less than 1TECU. The scatter arises for the most part from curvature of the individual segments, possibly reflecting imperfections in

the mapping process from slant to vertical arising from the protonospheric contribution on some ray paths at the lower elevations. However, it is demonstrated clearly that use of a low latitude cut-off provides compensation for the latitudinal asymmetry of the protonospheric electron content and that the SCORE process can recover the TEC to GPS altitude to an accuracy of about 1 TECU in these simulations.

The final column of values in Table 1 gives the calculated satellite plus receiver bias for the simulation up to GPS height but with the low latitude parameter set to 51.65°N. There is now good agreement between the arbitrary input and the consequent estimation of the value for each space vehicle, with the average difference over all of the satellites now only 0.1TECU. It should again be noted that the results shown here are representative of those obtained for each of the other satellite configurations used in the study.

**Experimental Results**

The work described above has relied on simulated observations generated by the SUPIM model. It has been shown that, with appropriate allowance for the protonospheric contribution, the SCORE process can yield diurnal variations in total electron content for a European mid-latitude station at solar minimum with a scatter to within about 1 TECU. In practice, experimental measurements are subject to other errors not taken into account in the model simulations. The SCORE process has been used on actual observations of GPS signals made at Aberystwyth. Sample results are presented in Figure 6. These are in the form of monthly averages of the diurnal curves for January 1997, with the error bars giving the standard deviations of the daily estimates at each time. The upper plot shows the results when all observations above 35° elevation are included. By contrast, the lower plot is based on output from SCORE with a lower latitude cut-off of 51.65°N imposed on the observations. It is clear that the values in the upper plot are larger by some 2 TECU, as would be expected from the model simulations. In addition, the standard deviations, reflecting day-to-day variability, are smaller in the lower panel and the night-time enhancement, which reaches the anomalously large value of 6 TECU in the upper plot, is greatly reduced below, where allowance is made for the protonospheric contents on the lower elevation rays from the south.

**Discussion and Conclusions**

Simulated slant electron contents generated from the SUPIM model have been used to test the SCORE procedure for obtaining TEC from GPS satellite observations. It has been shown that, when the plasma can be taken to be confined to the ionospheric section of the ray path below 1100km, the process gives excellent agreement, to a fraction of a TECU, with the input from the model. It should be noted that, while this condition may not always be valid for European observations at solar minimum, there are many circumstances in which the assumption can hold. The modelling studies of Lunt et al. (1998) showed that, because of the tilt of the Earth's magnetic field, the fractional contribution to the electron content arising from the protonosphere was much smaller for

observations at American longitudes than for European mid-latitude stations, even at the minimum of the solar cycle. The present work has demonstrated that use of all measurements with GPS ray path elevations greater than 35° results in TEC values erroneously high by some 2 TECU for Europe at solar minimum. However, any error resulting from similar analysis for American mid-latitudes at solar minimum, or more generally at solar maximum, is likely to be much smaller.

It should also be noted that, in the simulations reported here, the SUPIM model was run to represent conditions in which the protonospheric flux tubes had been filled from the underlying ionosphere for 16 days. In practice, the average time between geomagnetic storm-induced depletions of the flux tubes is much shorter (Kersley and Klobuchar, 1980), so that the results given here can be taken to be representative of as extreme conditions as are likely to be encountered in actual experimental situations.

It has been shown that, because of the asymmetry of the magnetic flux tubes with respect to the station at European mid-latitudes, it is possible to make allowance for the effect of the electron content on the protonospheric ray paths by omitting observations from some lower elevation ray paths equatorwards of the station from the analysis. This is an important result with possible more general application to techniques for obtaining TEC from GPS measurements. It has been demonstrated that, for the current study at a European location at 52.4°N, selection of a lower boundary for the IPPs of the ray paths 0.75° south of the station enables TECs to be measured accuracy of about 1 TECU. While this latitude difference will vary depending on the proportionate contribution from the protonosphere to the slant total electron content, Figure 4 shows that the resultant error in TEC from an inappropriate choice of the cut-off latitude is likely to be at the level of a fraction of a TECU, and thus of little significance to practical measurements. It should be noted that the results plotted in Figure 5 are for the individual satellites; if averages were taken of all available measurements at any given time then the errors would be reduced well below the 1 TECU of the scatter of the points. The scatter in the individual estimates of the TEC that limits the accuracy appears to result from imperfect mapping of the observations from slant to vertical, possible as a further consequence of the weighting of protonospheric electrons on certain ray paths. This is an area requiring further attention beyond the scope of the present work. In general, it can be concluded from the present study, that when appropriate steps are taken to compensate for plasma in the protonosphere, GPS observations can be processed by the SCORE technique to yield accurate estimates of satellite plus receiver biases and hence resultant TECs to better than 1 TECU.

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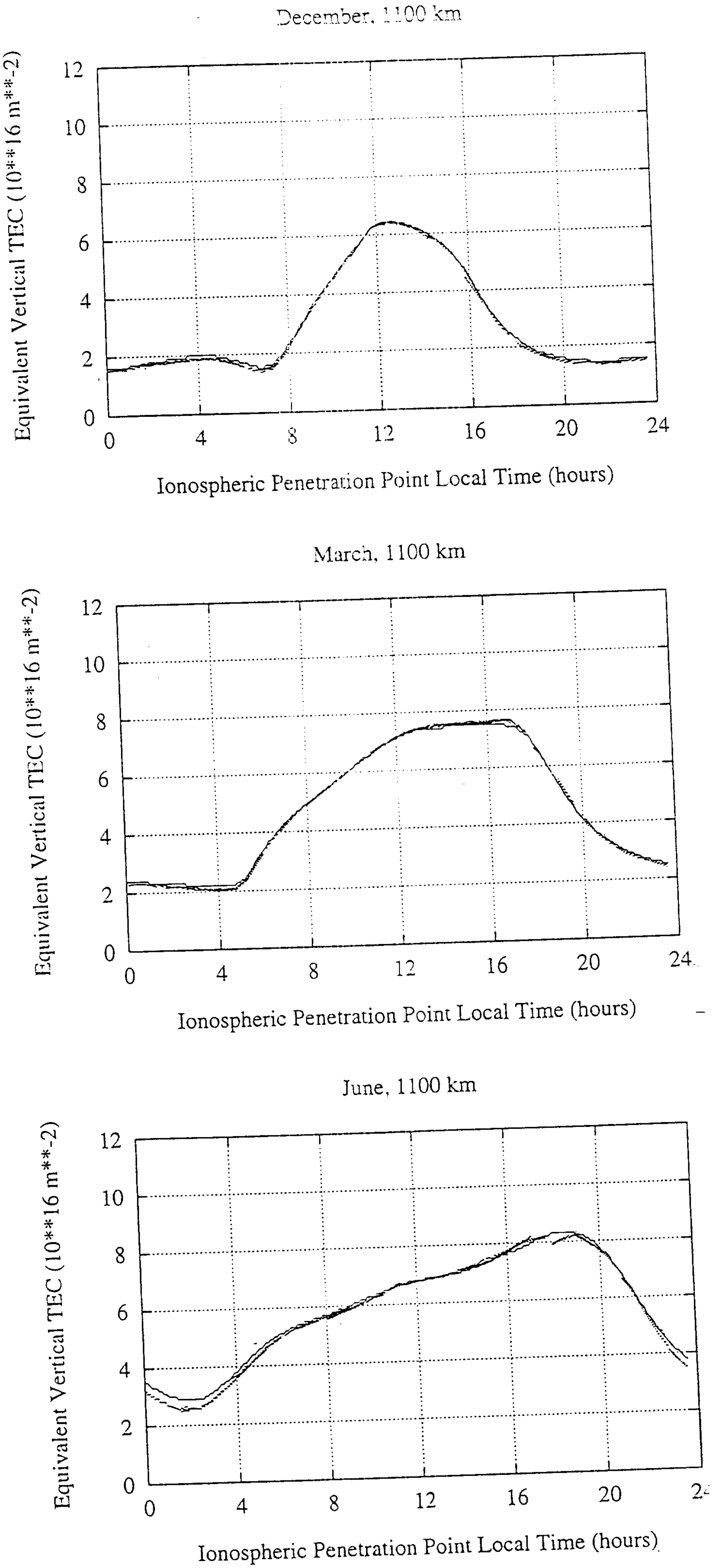



Figure 1. Example of accuracy of the SCORE process in a SUPIM simulation of the diurnal variation of equivalent vertical total electron content over Aberystwyth for winter, spring and summer at solar minimum. The solid lines give the vertical TEC obtained by integration of the electron densities estimated by the SUPIM model to an upper height of the 1100km. The dotted segmented curves show the resultant TEC output from the SCORE process for ray paths with IPPs in a one degree latitude band centred on the station.

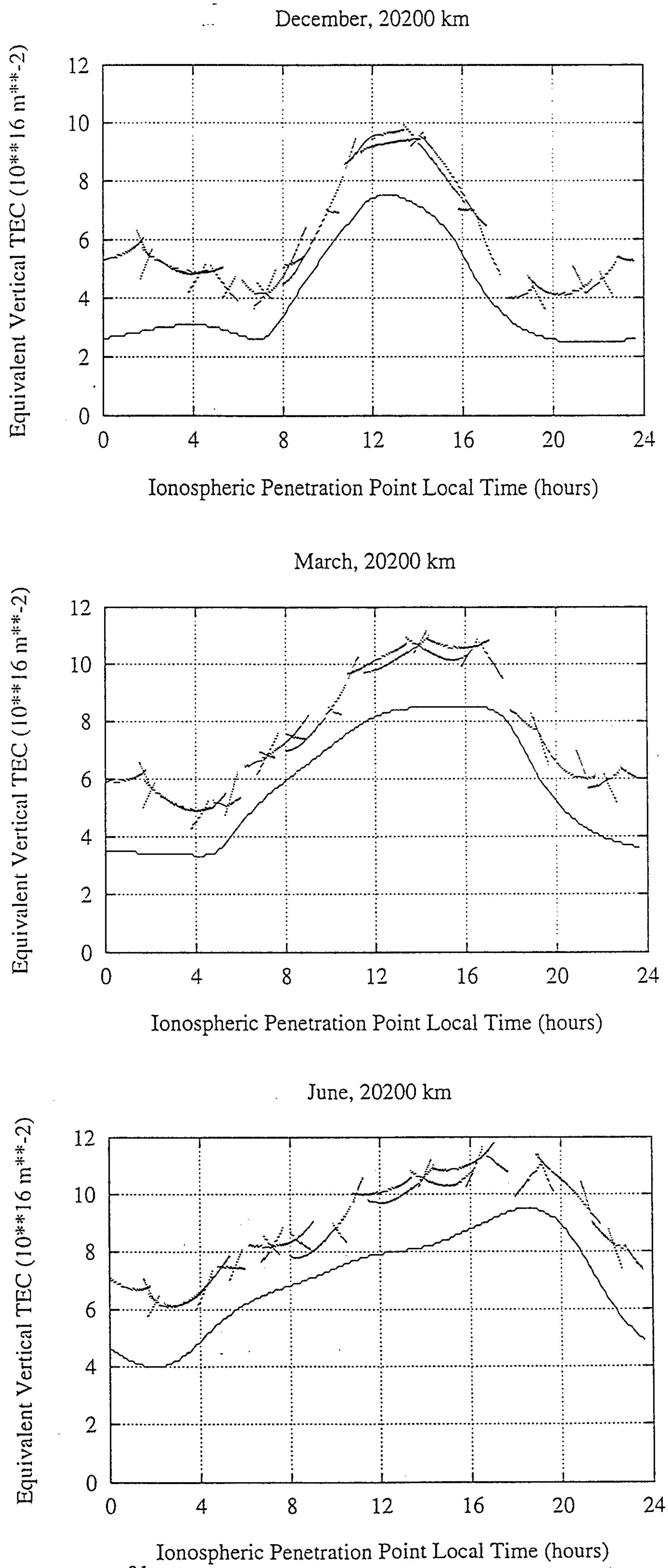



Figure 2. As for Figure 1, but with integration to GPS altitude of 20200km.

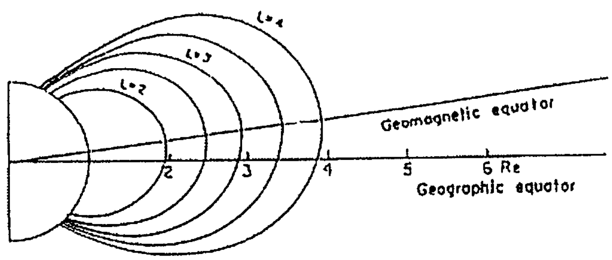
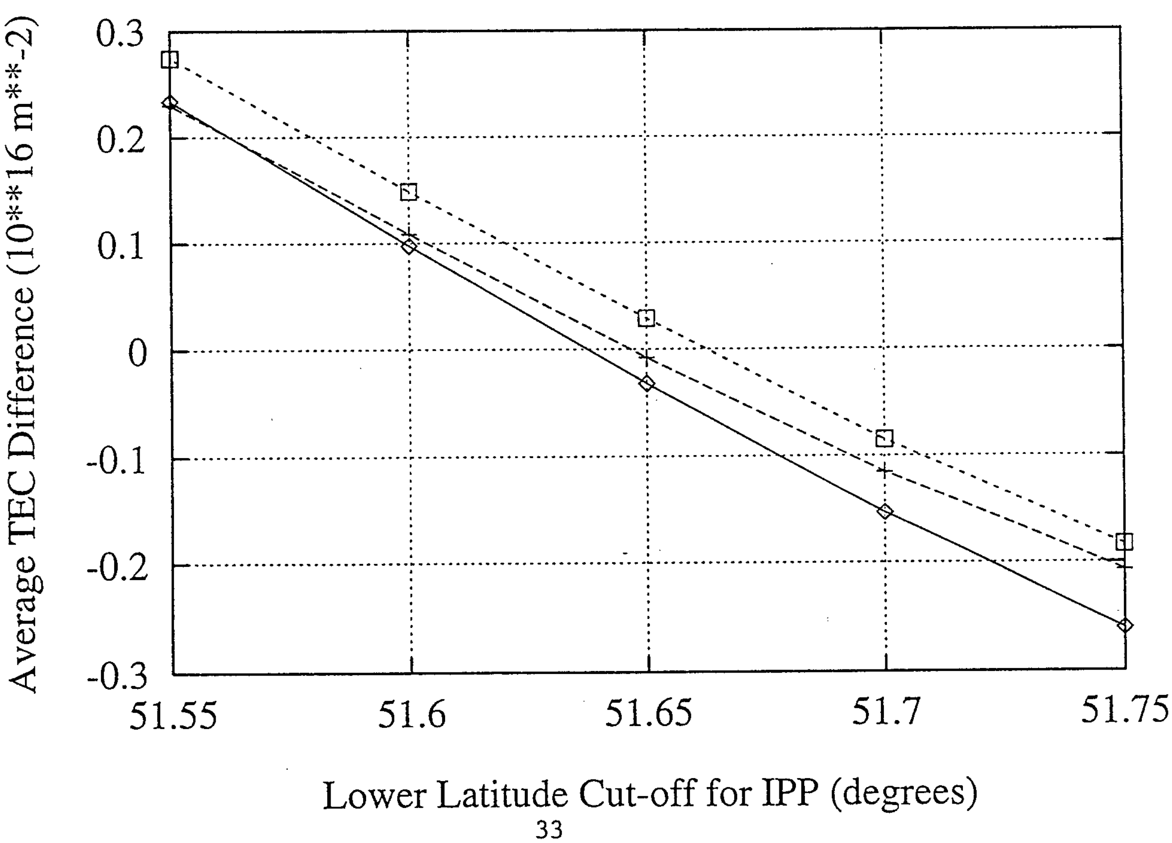



Figure 3. Diagrammatic representation showing the tilt of the protonospheric flux tubes appropriate to European longitudes.

Figure 4. The average difference between the TEC at Aberystwyth (52.4 °N) estimated by SCORE from that given by SUPIM for a range of lower latitude cut-off of the IPPs of the rays paths for the observations input to SCORE. The symbols refer to simulations of conditions in December (□), March (+) and June (◊) respectively.



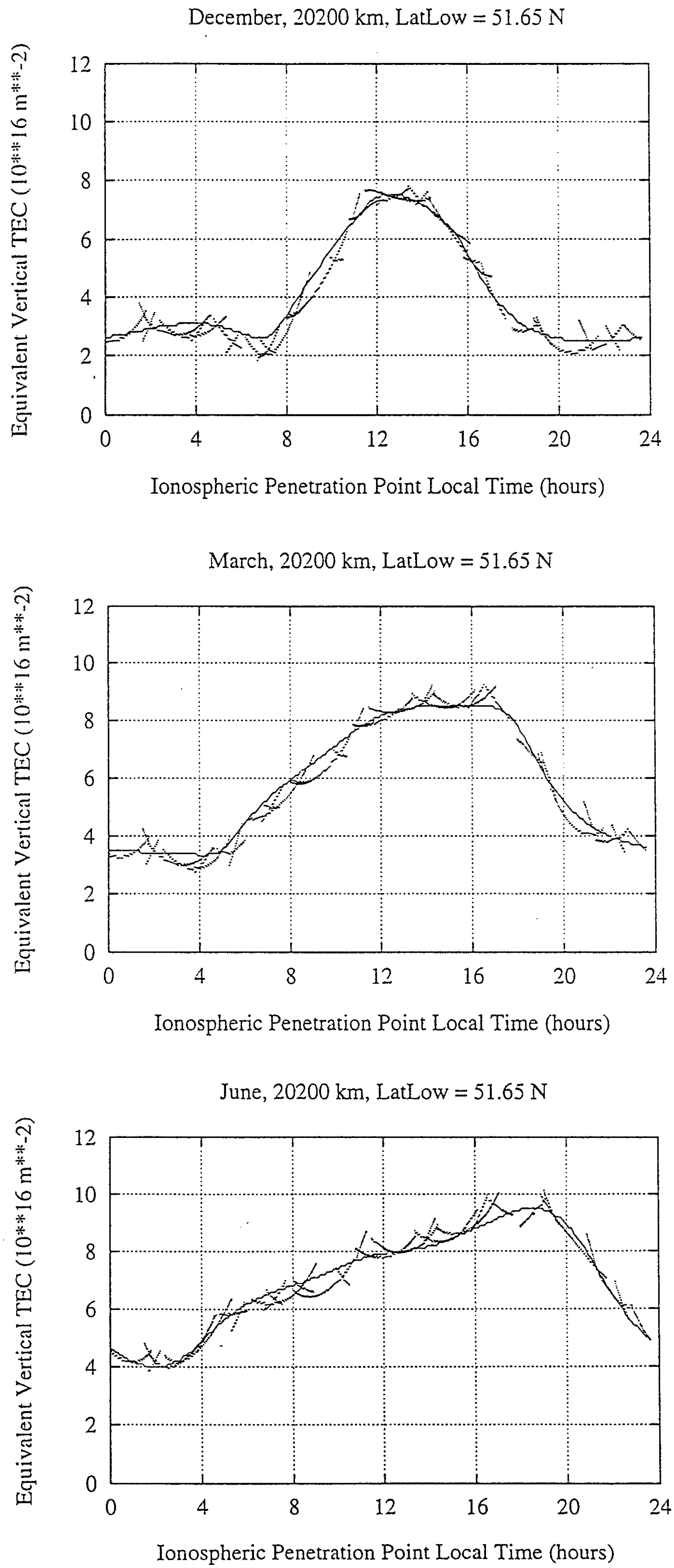



Figure 5. As for Figure 2, but with a restriction in the SCORE process to use of observations with ray path IPPs greater than 51.65°N.

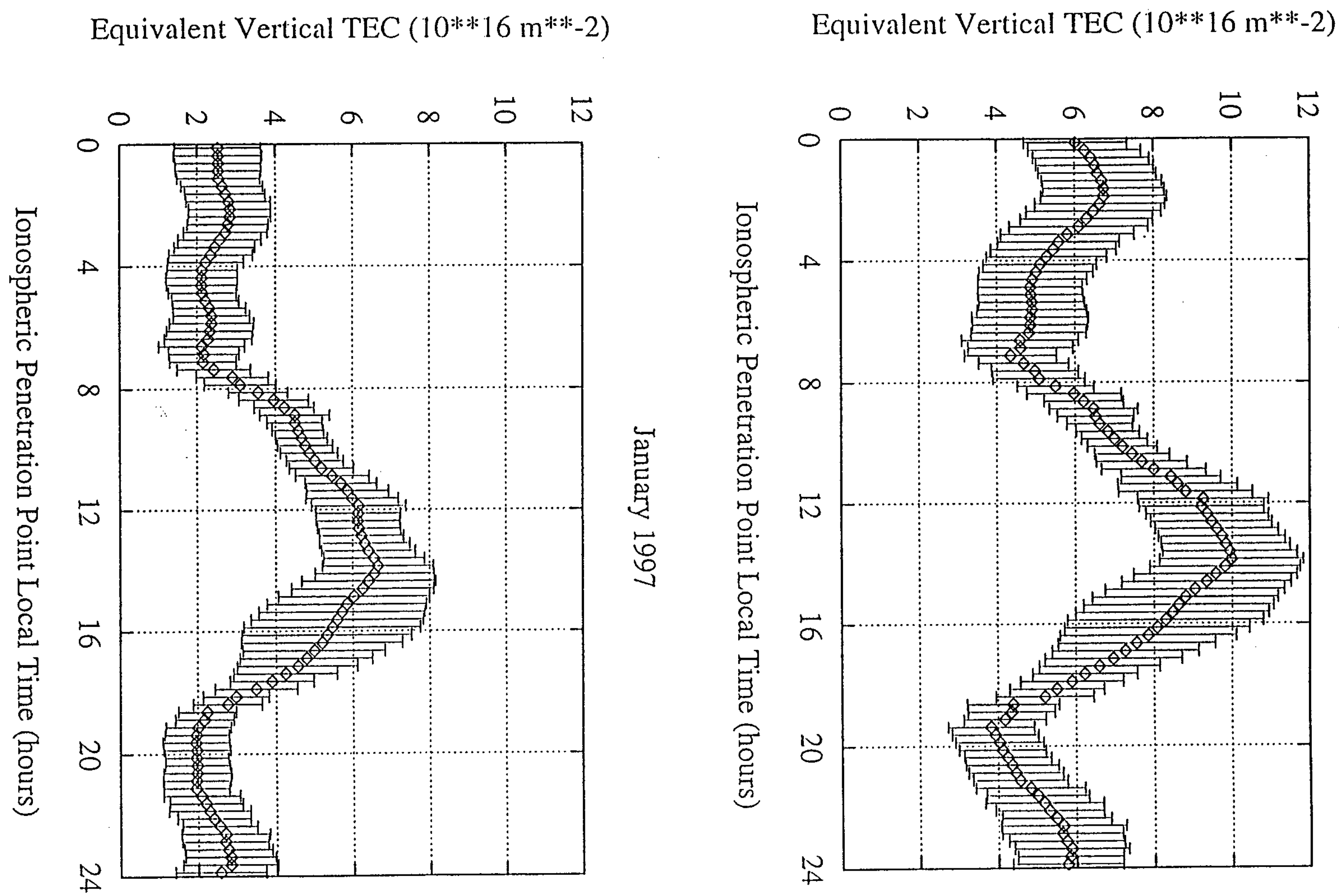



Figure 6. Diurnal variation of the average TEC estimated from actual GPS observations made at Aberystwyth in January 1997. For the upper panel, observations from all ray paths with elevations greater than 35 degrees were input to the SCORE process. For the lower panel only measurements from ray paths with IPPs at latitudes higher than 51.65°N were used. The error bars correspond to one standard deviation for the distribution of the values obtained for each day of the month.

| PRN | Bias in | NNSS LatLow=0 | GPS LatLow=0 | GPS LatLow=51.65 |
|---|---|---|---|---|
| 1 | 12.50 | 12.62 | 9.74 | 12.39 |
| 2 | 13.00 | 13.13 | 11.76 | 13.80 |
| 3 | 13.50 | 13.60 | 11.66 | 13.72 |
| 4 | 14.00 | 14.10 | 12.25 | 14.18 |
| 5 | 14.50 | 14.53 | 12.19 | 14.35 |
| 6 | 15.00 | 15.08 | 13.12 | 14.85 |
| 7 | 15.50 | 15.55 | 12.69 | 15.51 |
| 8 | 16.00 | 16.06 | 13.74 | 15.89 |
| 9 | 16.50 | 16.55 | 14.30 | 16.59 |
| 10 | 17.00 | 17.09 | 15.34 | 17.36 |
| 13 | 18.50 | 18.62 | 16.82 | 18.95 |
| 14 | 19.00 | 19.06 | 16.48 | 18.95 |
| 15 | 19.50 | 19.55 | 16.48 | 19.39 |
| 16 | 20.00 | 20.09 | 17.86 | 20.18 |
| 17 | 20.50 | 20.57 | 18.94 | 20.40 |
| 18 | 21.00 | 21.11 | 19.22 | 21.12 |
| 19 | 21.50 | 21.61 | 19.69 | 21.98 |
| 21 | 22.50 | 22.57 | 20.19 | 22.48 |
| 22 | 23.00 | 23.10 | 21.76 | 23.03 |
| 23 | 23.50 | 23.49 | 20.50 | 23.33 |
| 24 | 24.00 | 24.13 | 22.32 | 24.66 |
| 25 | 24.50 | 24.65 | 22.50 | 24.47 |
| 26 | 25.00 | 25.05 | 23.50 | 25.40 |
| 27 | 25.50 | 25.60 | 24.03 | 25.86 |
| 29 | 26.50 | 26.51 | 22.70 | 26.03 |
| 30 | 27.00 | 27.02 | 24.70 | 26.96 |
| 31 | 27.50 | 27.59 | 25.15 | 27.36 |
| Average Offset | | -0.08 | 2.11 | -0.10 |

**Table Caption**

Satellite plus receiver biases in TECU for individual satellites used in the simulations. The first column gives the satellite PRN. The second lists the arbitrary biases chosen for each satellite that were input to the analysis procedure. The biases estimated by SCORE are given in the remaining three columns. The first of these is for the simulation where all of the ionisation was assumed to be confined to the ionospheric section of the ray paths below 1100km. The second output column give the biases estimated when the protonospheric contribution to the electron content was included and all observations with elevations greater that 35 degrees were included. The final column relates to the case where only ray paths with IPPs north of 51.65 °N were included.

**Appendix C** Manuscript of paper on ' The contribution of the protonosphere to GPS total electron content: experimental measurements' submitted to Radio Science in November 1998 and accepted for publication with minor revisions in January 1999.

The paper describes results from experimental measurements made in UK in which estimates of TEC obtained from GPS observations, analysed by the modified SCORE process, are compared to TEC values determined using NIMS (formerly known as NNSS) satellites in 1100 km orbits. It is shown that the difference between the two types of measurements provides estimates of the protonospheric electron content that are in broad agreement with both the earlier modelling study and the known depletion and replenishment of protonospheric flux tubes in response to geomagnetic storm activity.

# The contribution of the protonosphere to GPS total electron content: experimental measurements

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***Abstract***

*GPS satellites have orbital altitudes of about 20200 km, while satellites in the NIMS constellation are in circular orbits at heights of about 1100 km. Independent measurements of the electron content in the ionised atmosphere can be made using the radio signals from both satellite constellations. Differences between the two estimates can be related to the electron content on the GPS ray paths above 1100 km, through the tenuous plasma of the protonosphere. Results are reported from some 21 months of simultaneous observations of both GPS and NIMS transmissions at a European mid-latitude station at solar minimum. It is shown that the average differences between the electron contents measured by the two systems are in broad agreement with the predictions from an earlier modelling study of the effects of the protonosphere on GPS total electron content. The expected influence of ray path / flux tube geometry and the rapid depletion and slow refilling of the protonosphere in response to geomagnetic storm activity can be seen in the averaged measurements.*

## Introduction

The GPS satellite navigation system is subject to inaccuracies due to the effects of the ionised atmosphere on the propagation of the radio signals. Correction for the ionospheric electron content can, in principle, be made when dual frequency receivers are used. However, with systems based on relatively inexpensive single frequency receivers compensation for propagation effects requires the use of ionospheric models. Such models, usually based on measurements of total electron content or maximum plasma density, normally represent only the bulk of the plasma in the ionospheric F2-layer at heights of a few hundred kilometres. The GPS satellites have orbital altitudes of about 20200 km so that the rays have long paths through the tenuous hydrogen-based plasma of the protonosphere, well above the much denser ionosphere. The effects of the protonosphere on GPS systems have been largely neglected and it is only recently that significant effort has been devoted to investigating the total electron content on ray paths

through this region. Lunt et al.(1998a) have studied the contribution of the protonospheric ray paths to GPS electron content by means of simulations using the Sheffield University Plasmasphere Ionosphere Model (SUPIM). It was demonstrated that, in general, the total electron content above 1100 km amounts to only a few TECU (1 TECU≡$10^{16}$ electrons m $^{-2}$), with the geometry of the magnetic field-aligned flux tubes of the Earth's plasmasphere resulting in the greatest contribution on ray paths to the south of a station at European mid-latitudes. It was also shown that, though small in absolute terms, the protonospheric electrons could make up more than 50% of the total for some ray paths to European stations at solar minimum.

The present paper aims to complement the modelling study, by reporting an attempt to determine experimentally the electron content on the protonospheric section of the GPS ray paths. The method used was to investigate the difference between measurements of total electron content obtained by two independent techniques. Estimates of total electron content have been recovered from observations of dual frequency GPS transmissions using the Self-Calibration Of pseudo-Range Errors (SCORE) technique (Bishop et al., 1996), whose accuracy was initially verified using independent measurements (Bishop et al., 1997a) and validated in an early modelling study (Lunt et al., 1998b). The GPS measurements contain contributions from both ionospheric and protonospheric sections of the ray paths. Experimental observations have also been made of the electron content in the ionosphere by monitoring signals from satellites in the Navy Ionospheric Monitoring System (NIMS) at altitudes of about 1100 km. Differences between the two estimates give a measure of the electron content on the protonospheric part of the GPS ray paths.

**Experiment**

The experimental observations were made at Aberystwyth (52.4°N, 4.1°W), covering a total of some 21 months in 1996, 1997 and 1998. A dual-frequency receiver logged signals from GPS satellites that were analysed by the SCORE process to yield measures of equivalent vertical total electron content at one minute intervals. Observations of ionospheric electron content are made routinely at Aberystwyth using signals from NIMS satellites, as part of a project involving tomographic imaging of ionospheric electron density. The NIMS satellites, in circular polar orbits at altitudes around 1100 km, transmit phase coherent signals from which electron content can be estimated as a function of latitude as the satellite passes from horizon to horizon. Absolute values of electron content are obtained by a well-established method of matching observations made at two or more stations separated by several degrees of latitude. For the earlier studies described here the Aberystwyth observations were complemented by those at a station some 3 degrees latitude to the north, in the south of Scotland. However, for most of the work the calibration was obtained from simultaneous measurements at 5 locations spanning the entire latitude range of UK.

Figure 1 shows an example of equivalent vertical ionospheric electron content as a function of latitude obtained from calibrated observations of a NIMS satellite pass made at 5 stations in UK.

## The SCORE Process

The SCORE concept is to use a self-consistency constraint on the receiver's own measurements of ionospheric delay to derive the *sum of the receiver system and satellite pseudorange errors* and thus the corrected slant absolute TEC, for each satellite. The self-consistency constraint is illustrated by considering a "conjunction" occurring between two satellites, that is, an event where both satellites appear to arrive at the same moment at a point where their observed paths cross. If such an event were to occur, the same ionospheric pseudorange error (TEC value) should be seen for each satellite. The SCORE process works by requiring maximum agreement in TEC measurements at all satellite "conjunctions", where a "conjunction" is actually a defined correlation region in latitude and local time at the ionospheric penetration point (IPP LT). SCORE uses 24 hours of data from a single receiver, operates without using any test signal, does not assume any model ionosphere, or require the application of data from an observing network.

In an earlier modelling study, Lunt et al.(1998b) validated the use of the SCORE process to determine accurate estimates of total electron content from GPS observations. It was shown that for observations at European mid-latitudes, it was necessary to restrict the use of measurements from ray paths to the south in the analysis procedure, to compensate for the protonospheric electrons. A lower latitude cut-off of 0.75 degrees south of the station was shown to be appropriate for the ionospheric penetration points of the ray paths to Aberystwyth. This value was used in the present study. A useful application of the protonospheric asymmetry, for which the above cut-off is compensating, has lead to a new technique for measuring protonospheric TEC, (Bishop et al., 1997b).

An example is given in Figure 2 of the form of the output obtained from SCORE. It shows a diurnal plot of equivalent vertical total electron content, for an ionospheric latitudinal band of 1 degree centred on Aberystwyth, made up from segments of observations of many GPS satellites. Plots of this kind were used to obtain average values of total electron content for each 15 minute time interval throughout the day. It should be noted that in both Figures 1 and 2, which refer to the same day, the latitude referred to is that of the ionospheric penetration point (IPP) of the ray path at 350 km altitude, while for the GPS observations the time is characterised as the local time of the IPP defined in this way.

## Results

The diurnal plots obtained from SCORE were used to estimate the equivalent vertical total electron content up to GPS altitude (GPS TEC) at IPP times corresponding to NIMS satellite passes. Figure 3 shows scatter plots of GPS TEC against the corresponding estimates of equivalent vertical ionospheric electron content (NIMS TEC) obtained from each of the passes of the NIMS satellites where data were available in March 1997. The four plots correspond to IPPs of GPS rays with latitudes in bands one degree wide and centred as shown. The data points are sparser away from the overhead situation. The

NIMS TEC was estimated at latitudes corresponding to the mid-point of each of the bands. It can be seen that the scatter plots show a high degree of correlation between the two independent estimates of the TEC, in particular for the latitudinal band centred overhead of the GPS receiver site where the number of the observations was greatest. The two lines drawn on each of the plots correspond to the best-fit line and the best-fit line with unity gradient, respectively. It can be seen that the two linear fits map each other very closely, with significant difference only to be found in the highest latitude band where the scatter of the individual points is slightly larger than in the other plots. Examination of the intercepts of the best-fit lines for the four plots shows a progression with latitude. For the 50.4°N band the intercept shows that the GPS TEC values exceed those from the NIMS observations by some 2 TECU. This value has reduced to 1 TECU at 51.4°N and is close to zero for the band overhead of Aberystwyth centred on 52.4°N. For IPP latitudes centred one degree to the north of the station (53.4°N) the intercept of the unity gradient line is again zero. The intercept represents the excess of the GPS TEC over the NIMS TEC and so can be interpreted as arising from the plasma above 1100 km. The progression of the intercepts seen in Figure 3. The decreasing electron content attributable to the protonospheric ray paths with increasing latitude agrees with the predictions from the SUPIM model made by Lunt et al. (1998a), though the absolute magnitudes of the measurements are less than those given by the model. Confirmation of this trend with latitude can be seen in Figure 4. Here the average differences between corresponding measurements of GPS TEC and NIMS TEC are plotted for the four latitudinal bands. The averages have been calculated from the estimated differences for all of the experimental measurements made in simultaneous observations using both satellite systems in 1996, 1997 and 1998. The error bars shown represent the standard errors of the mean values, estimated from more than 2500 individual values in the case of the overhead latitudinal band. The small size of the error bars demonstrates the statistical significance of the mean values, even though the individual measurements are subject to large errors. It can be seen from Figure 4 that, for ray paths with IPPs two degrees to the south of Aberystwyth, the contribution of protonospheric electrons above 1100 km altitude is equivalent on average to an additional 1.6 TECU in the equivalent vertical total electron content. This value has reduced to about 0.75 TECU for IPPs in the latitudinal band one degree south of the station. Directly above Aberystwyth, the GPS ray paths between 1100 km and 20200 km only yield an additional content of about 0.05 TECU. For ray paths intersecting the ionosphere one degree to the north the protonospheric electron content is almost zero.

The general form of these results is in broad agreement with the predictions of Lunt et al. (1998a). The modelling work indicated that for observations at a station like Aberystwyth ray paths to the south would intersect plasmaspheric flux tubes with significant electron densities. By contrast, the geometry of the geomagnetic field is such that to the north most of the GPS ray path above the ionosphere is encountering high L-shell flux tubes outside the plasmapause, with very low electron densities and consequently almost zero additional electron content. It can be noted that the modelled values were in general larger than those determined experimentally. However, the model study simulated a filling of the protonospheric flux tubes from the underlying ionosphere for 16 days, while in

practice the geomagnetic storms that deplete the protonospheric plasma recur on a more frequent interval so that there is less time for the ionisation to build up.

The basic physics of plasmaspheric processes was outlined by Lunt et al. (1998a), with appropriate references. In essence, the ionospheres in conjugate hemispheres act as sources of plasma, with the interconnecting flux tube forming a protonospheric reservoir. There is some diurnal interchange between ionosphere and protonosphere, with downward diffusion from the latter helping maintain the night-time F2 layer. However, the broad trend is towards a gradually filling of the larger volume flux tubes on the higher L-shells within the plasmapause. Geomagnetic storm activity causes rapid contraction of the plasmapause and depletion of the flux tubes. A gradual replenishment of the protonospheric flux tubes then takes place from the underlying ionosphere over a period of many days (Kersley et al., 1978; Kersley and Klobuchar, 1980). The underlying physics indicates that the diurnal interchange between ionosphere and protonosphere may be significant, particularly on lower L-shell flux tubes. Nevertheless, the modelling studies reported by Lunt et al. (1998b) suggested that there is likely to be little diurnal variation of the protonospheric electron content integrated along GPS ray paths for many of the geometries investigated. The differences between the experimental measurements of GPS TEC and NNSS TEC obtained in the present study were assembled into eight 3-hour bins of IPP local time. The resultant plots of the diurnal variation of the mean electron content above 1100 km are shown in Figure 5 for the four latitudinal band of the SCORE output. Here again, all of the observations have been averaged, without regard to season or year. It can be seen that the curves are again ordered according to latitude, as expected from the ray path / flux tube geometry. There appears to be some evidence for a diurnal variation with a minimum about 0800 IPP LT and a maximum at 2000 IPP LT. These times could correspond respectively to a dawn minimum, following downwards flow from protonosphere to ionosphere at night, and a maximum at about the time of greatest electron density in the ionospheric F-layer in summer. However, the magnitude of the error bars, representing one standard deviation of the data points, must be noted. A point of concern is that small negative values are seen for the two higher latitude bands at night, a physically impossible situation. It thus must be concluded that there is some small but systematic error in the analysis procedure. Lunt et al. (1998b) examined the validity of the SCORE process in detail, particularly in relation to minimising the errors resulting from long ray paths through the protonosphere equatorwards of the station. However, it was noted in that simulation that there was still scatter in the output, possibly arising from imperfect mapping from slant to vertical in a thin shell ionospheric model. Further investigation is beyond the scope of the present work, but it may be that there are systematic errors in the SCORE process, possibly linked to longitudinal gradients in the post-dawn and evening ionospheres or latitudinal gradients associated with the walls of the main trough, that contribute to the diurnal variations seen in Figure 5. It was also thought that another possible explanation for the negative values at night and at least part of the diurnal variation seen at the higher latitudes, could lie with the analysis of the NIMS measurements. The slant measurements were converted to equivalent vertical using a constant assumed ionospheric height of 350 km. In reality the centroid height of the ionisation undergoes the well-known diurnal variation. Limited studies showed that a

more realistic choice of height can introduce small changes in the estimated equivalent vertical TEC. However, the sense of variation would not be in agreement with the results of Figure 5. It can probably be concluded that there is some evidence for a small diurnal exchange between ionosphere and protonosphere to be found from the current results, though the magnitude is likely to be less than that shown in Figure 5.

It was considered that evidence in the GPS/NIMS data of the present study of a depletion and refilling following geomagnetic storm activity would provide additional and conclusive proof that it was the protonospheric contribution that was being measured.

All of the GPS TEC minus NIMS TEC measurements were subject to a superposed epoch analysis, based on sudden commencement geomagnetic storms. The results are presented in Figure 6, with the day of the sudden commencement being designated as day 0. Plots are shown for the four latitudinal bands of the SCORE analysis, representing averages of all observations within the 24-hour blocks, with error bars giving standard errors. It can be seen that for the lowest latitude band, the average protonospheric TEC was about 1.6 TECU on the day prior to sudden commencement. It can be noted that this value agrees well with that plotted for day 10, which was an average for the large body of data relating to 10 or more days after storm onset. An increased protonospheric content can be seen at this latitude on the day of sudden commencement itself, with the value rising to just over 2 TECU. However, on the day following the start of the storm the magnitude of the protonospheric content almost halves, clear evidence of the depletion of the plasmasphere. The gradual refilling of the protonospheric flux tubes can be inferred from the rising trend in the content apparent on subsequent days. However, it should be noted that because of the random occurrence of sudden commencement storms successively fewer data values were available for the determination of the means up to day 9. Confirmation of the storm-time pattern, with enhancement on the day of commencement followed by rapid depletion and gradual refilling, can also be seen in the results for the latitudinal band centred on 51.4°N, one degree to the south of the station. The results for ray paths both in the overhead sector and to the north do not show clear evidence of a consistent pattern, all being clustered essentially close to zero. These findings are in keeping with the ray path / flux tube geometry and confirm the earlier results that the protonosphere makes little contribution to the GPS TEC directly above and to the north of Aberystwyth. It should again be noted that there are a few mean values that are marginally negative, but only at about the 0.2 TECU level. Since it is physically impossible for a precise measurement of the NIMS TEC to be less than that for an exactly corresponding GPS TEC, these values must be representative of errors in the determination process. However, the conclusion can be reached from Figure 6, that the differences between the electron contents measured using GPS and NIMS do contain signatures consistent with the expected behaviour of protonospheric depletion and replenishment in response to geomagnetic storm activity.

**Discussion and Conclusions**

Experimental observations have been made of total electron content using radio transmissions from both GPS and NIMS satellites. The differences between

measurements obtained by the two techniques, for corresponding ray path ionospheric penetration point latitudes, have been interpreted in terms of the contribution of the protonospheric electrons above 1100 km. The results are in broad agreement with the predictions made by Lunt et al. (1998a), particularly in relation to the geometrical aspects of the ray path / flux tube interaction. It is clear that there is a small contribution from the protonosphere at the level of 1 to 2 TECU in GPS TEC observations to the south of the European station, under the solar minimum conditions of the present study. However, directly above and to the north of the station the protonospheric content is minimal.

Experimental results of direct relevance to the current investigations are those of Ciraola and Spalla (1997). These workers made observations of both GPS and NIMS (previously known as NNSS) TEC from sites in southern Italy over several years. They report an average difference between the two measurements of $3\pm1$ TECU. This result is broadly in line with the current study, bearing in mind that it refers to European observations some 10 degrees further south in latitude, but still essentially at solar minimum. Ray paths from Italian stations will intersect lower L-shell flux tubes with higher electron densities than those encountered in the present experiments.

Kersley and Klobuchar (1978) presented results of protonospheric content, obtained at Aberystwyth from observations using the ATS-6 geostationary satellite in 1975/6. The ray path elevation was less than $30^{\circ}$ so that the results were taken to be dominated by conditions on a flux tube with $L \sim 1.7$. Slant protonospheric contents around 3 to 5 TECU, with a weak diurnal variation were found, for these European observations at solar minimum. The current results, relating to higher L-shells, are broadly in keeping with the ATS-6 study.

Kersley and Klobuchar (1980) used the ATS-6 observations to investigate storm associated protonospheric depletion and recovery. The results for Aberystwyth showed a rapid depletion of some 1 to 2 TECU during the evening of the sudden commencement day, followed by a gradual replenishment over many days up to the next storm. Here again, bearing in mind the differences in ray path / flux tube geometry, the present results are in general agreement with this earlier study.

The general conclusion to be reached from the current investigation is that differences in measurements of TEC by the GPS and NIMS techniques can yield average information on the protonospheric electron content. However, the magnitude of the protonospheric contribution is small in the case of the present observations made at European mid-latitudes at solar minimum. The study demonstrates that it is possible to estimate experimentally the effect of the protonospheric electron content on GPS measurements. While the contribution is small under the present conditions of low solar activity it could assume greater importance as the maximum of the solar cycle is reached.

*Acknowledgements*

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Figure 1. Example of equivalent vertical TEC as a function of latitude obtained from observations during a pass of a NIMS satellite made at 5 stations in UK.

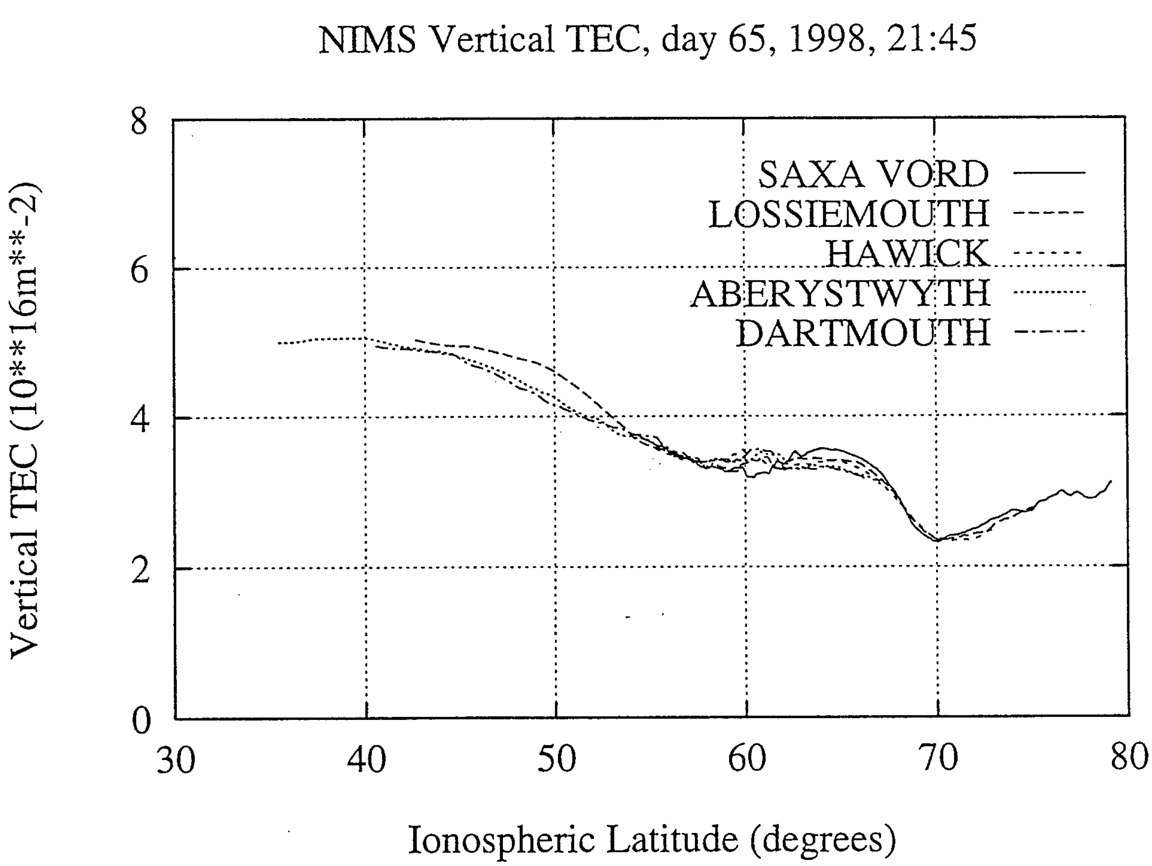


Figure 2. Example of the diurnal variation of equivalent vertical TEC obtained using the SCORE process on observations of GPS satellites made at Aberystwyth. The segments of the curve relate to ray paths from individual satellites with ionospheric penetration points at 350 km altitude lying within a one degree latitude band centred above the station at 52.4°N.

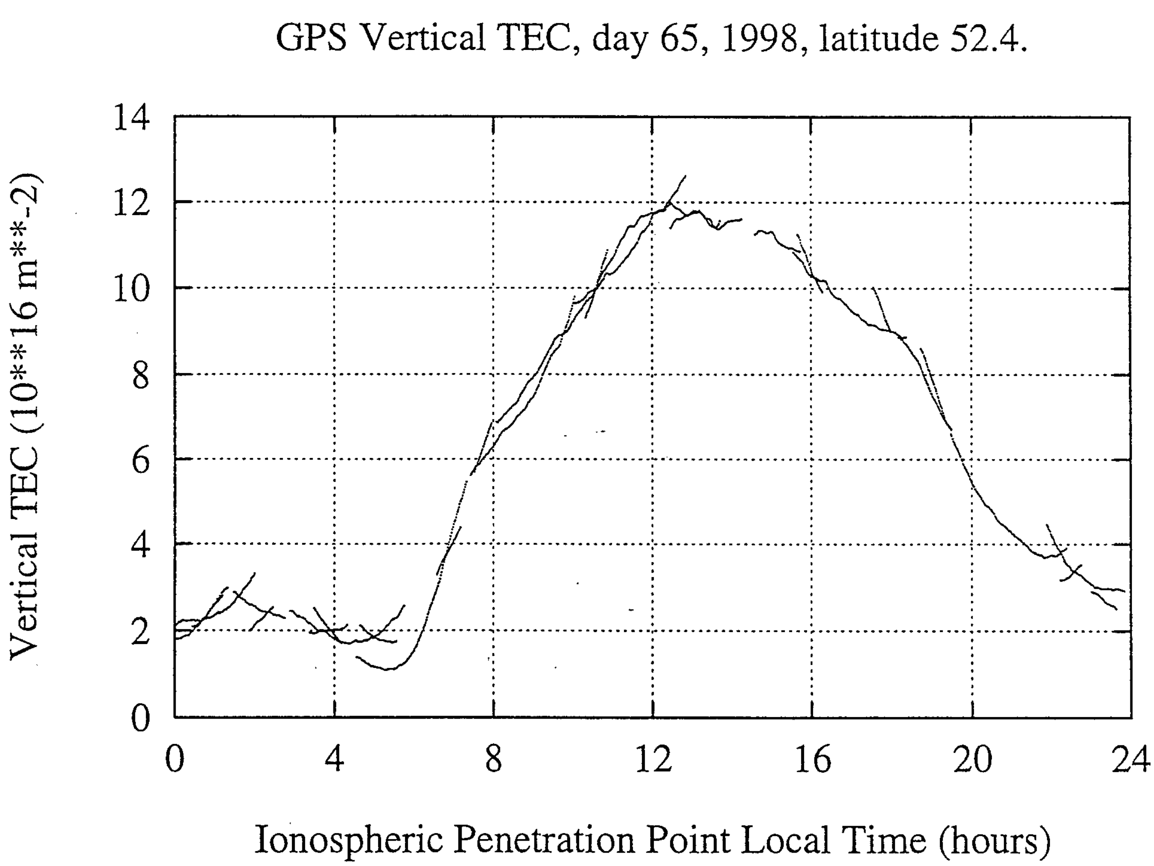


Figure 3. Scatter plots of GPS equivalent vertical TEC against NIMS equivalent vertical TEC for IPPs in one degree bands centred on the four latitudes shown. The best fit line is depicted by (——), while the best fit line with unity gradient is shown by (---).

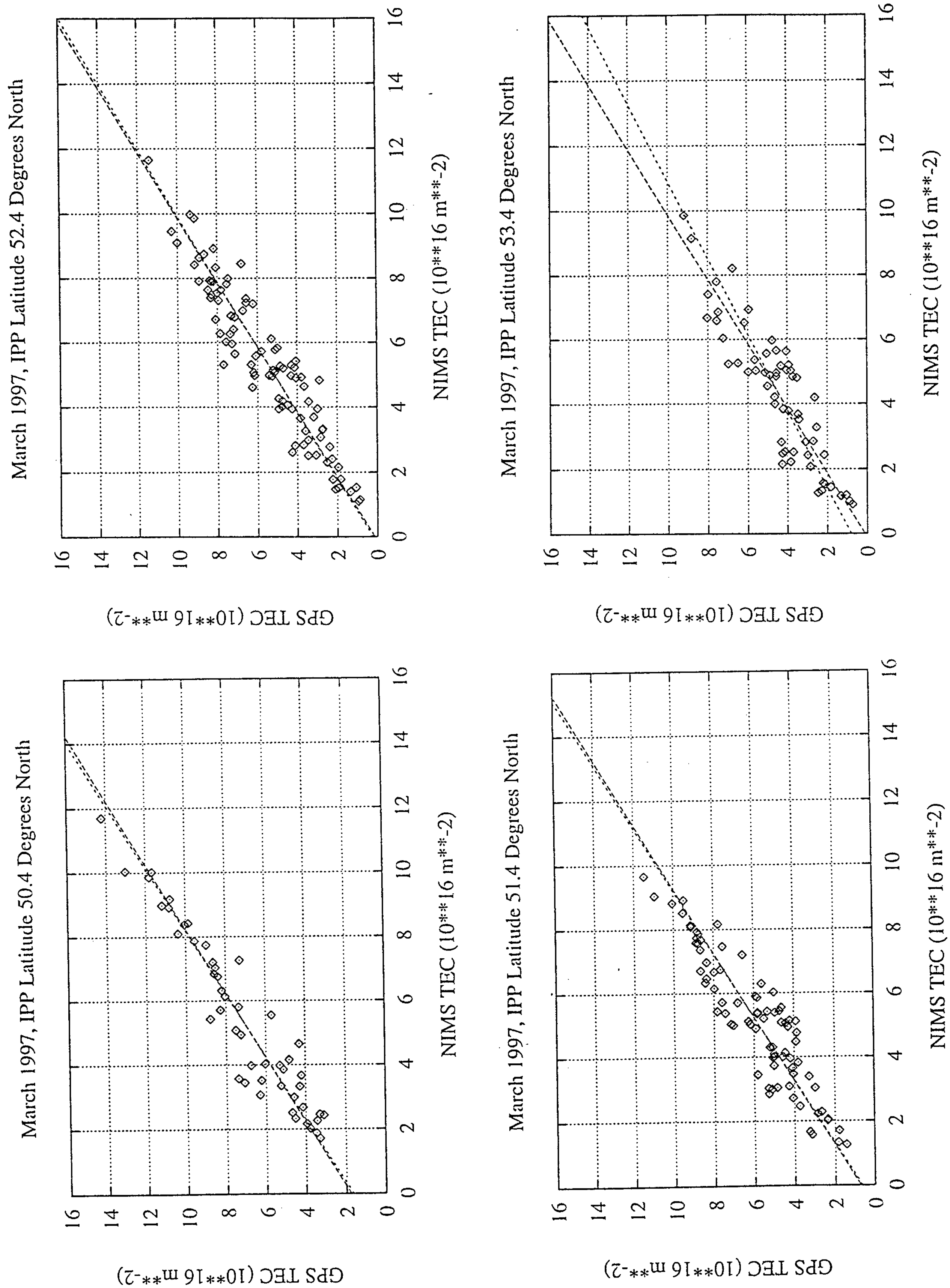


Figure 4. Average difference between GPS equivalent vertical TEC and NIMS equivalent vertical TEC as a function of IPP latitude. The error bars denote the standard errors of the means for all simultaneous measurements during the 21 months of the present study.

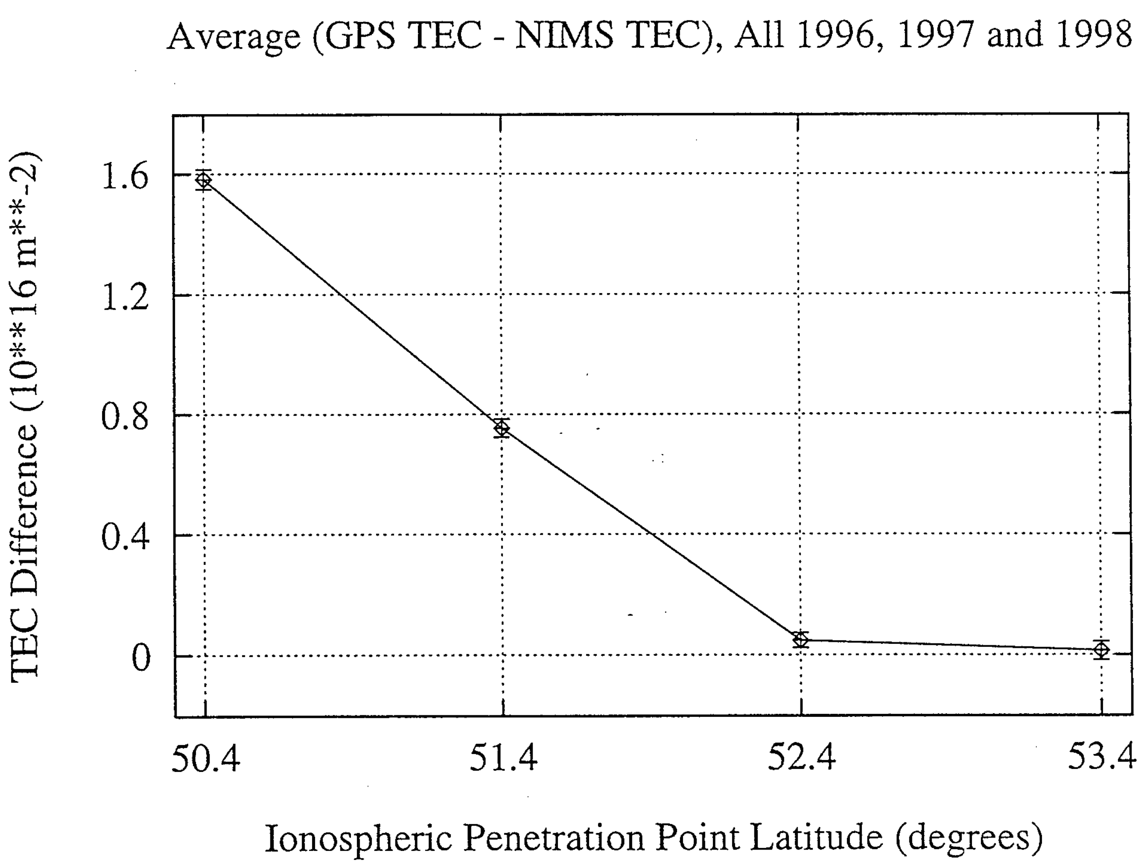


Figure 5. Diurnal variation of the average differences between GPS TEC and NIMS TEC for the four latitudinal bands centred on 50.4° N (—), 51.4° N (—), 52.4°N (---) and 53.4°N (....).

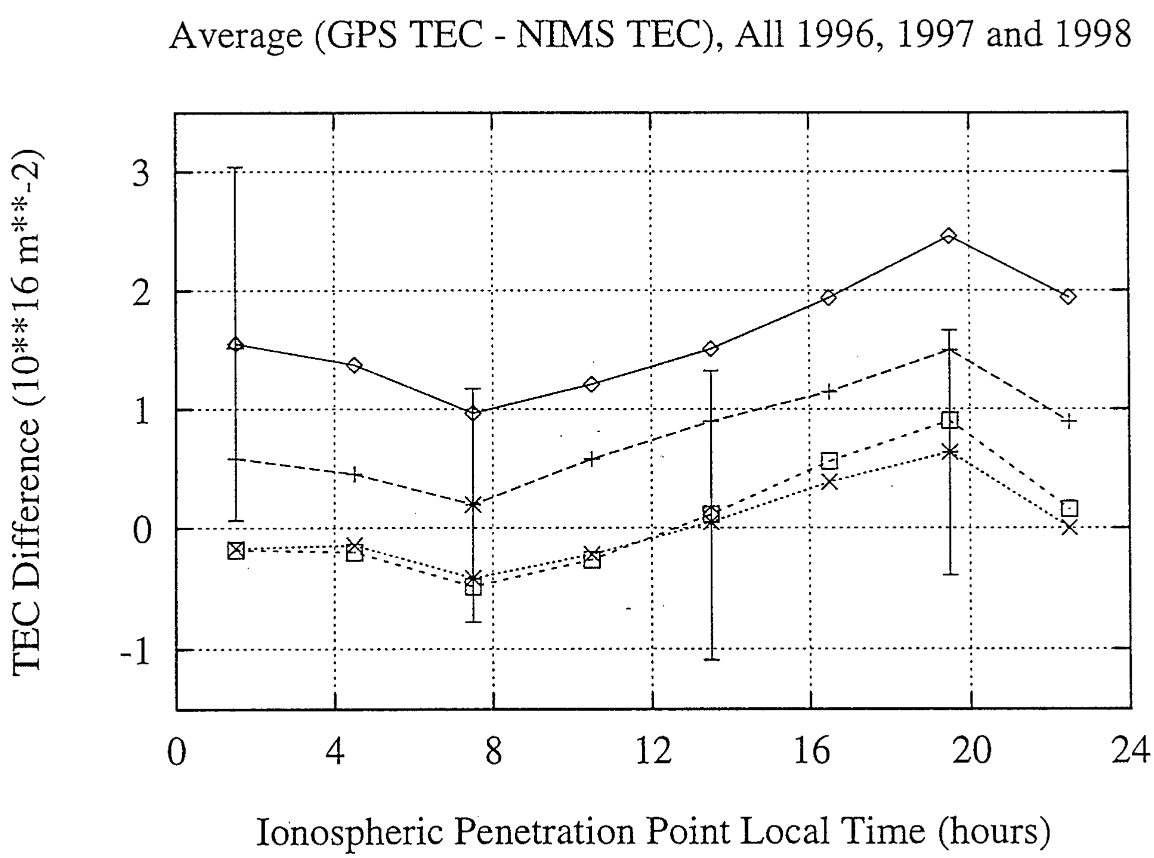
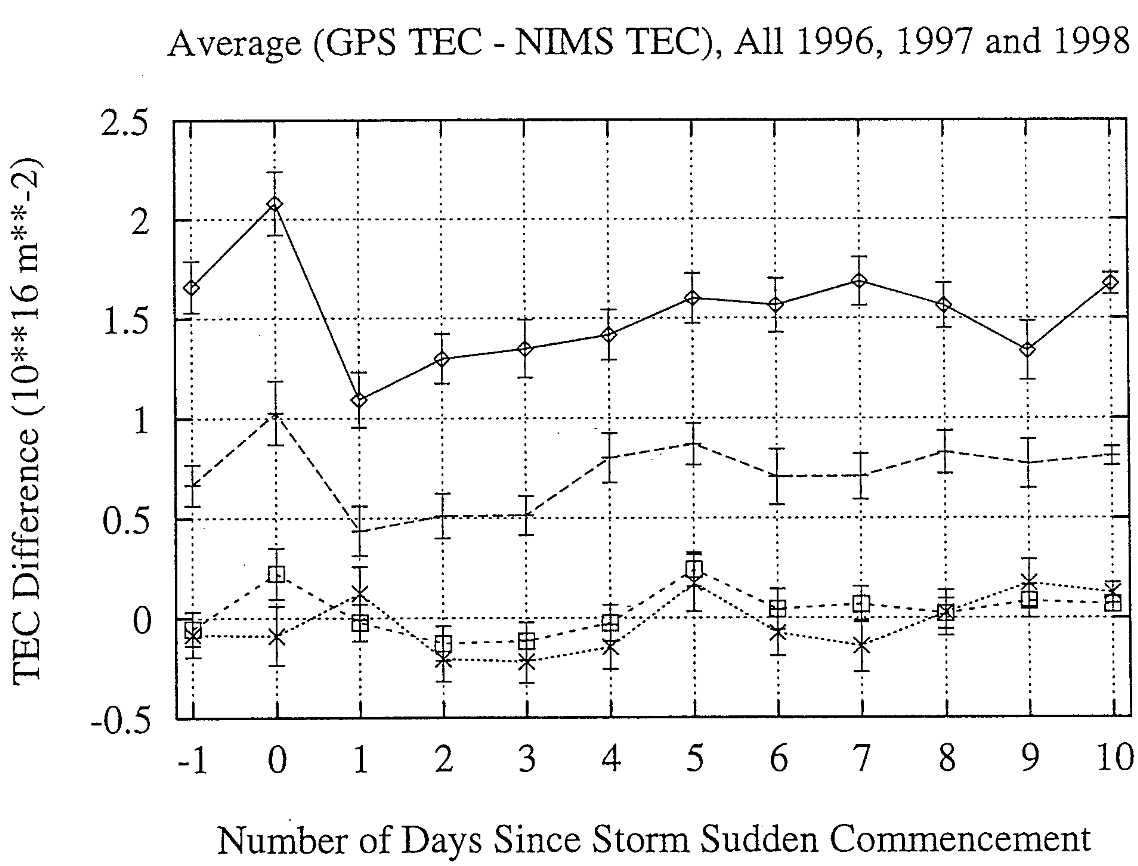


Figure 6. Superposed epoch analysis of average difference between GPS TEC and NIMS TEC as a function of number of days since storm sudden commencement, for the four latitudinal bands centred on 50.4° N (—), 51.4° N (—), 52.4°N (---) and 53.4°N (....).



**Appendix D** Manuscript of paper on 'The protonospheric contribution to GPS TEC: two-station measurements' submitted to Radio Science in December 1998.

The paper describes an experiment in which GPS observations were made at two stations in UK separated by some 2 degrees of latitude. The resultant TEC measurements for the common ionospheric band between the stations, obtained by the modified SCORE process, have been compared in a study of the effect of the asymmetric protonosphere on GPS observations. It is shown that the measured difference between the TECs is in broad agreement with that predicted by the SUPIM model.

## The protonospheric contribution to GPS TEC: two-station measurements

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*Abstract*

*Results are presented from an experiment to estimate the contribution of plasma on ray paths through the protonosphere to measurements of total electron content using GPS signals. Simulations using the SUPIM model show that observations of GPS satellites made at two stations separated by a few degrees of latitude could involve a common ionospheric volume, but very different intersection geometries of the ray paths with protonospheric flux tubes. Experimental results demonstrate that on average higher equivalent vertical TECs are measured on ray paths to the south than to the north of the European mid-latitude stations considered here. The observations are discussed in terms of the known asymmetries of the protonospheric flux tubes and caution is advised in the use of thin shell ionospheric models for precise determination of TEC or correction for its effects on GPS systems.*

### Introduction

Single frequency use of the GPS satellite navigation system is subject to errors due to the effects of the ionised atmosphere on the propagation of the radio signals. Correction for the ionospheric electron content often relies on models, based essentially on average behaviour of the ionospheric F2-layer. However, the signals from the GPS satellites in orbit at about 20200km altitude have long ray paths through the tenuous plasma of the protonosphere well above the bulk of the ionisation. No account is taken of the protonosphere in the ionospheric models used for GPS, and little has been known about the electron content in this region and its possible effects on GPS systems.

The present paper culminates a series, reporting studies aimed at addressing the potential problem of the protonosphere to GPS users. Lunt et al. (1998a) described simulations using the Sheffield University Plasmasphere Ionosphere Model (SUPIM), in which the protonospheric electron content was assessed for typical ray path geometries from GPS

satellites to mid-latitude stations. In a subsequent paper, Lunt et al. (1998b) used simulated observations from SUPIM to validate the use of the Self-Calibration Of pseudo-Range Errors (SCORE) analysis procedure for estimating total electron content (TEC) from GPS observations, in the presence of protonospheric electrons. Experimental measurements of protonospheric electron content, made over a period of 21 months by differencing GPS TEC from corresponding estimates made using the low orbit NIMS satellite system, were presented by Lunt et al. (1998c). In this final paper, results are reported from an experiment in which protonospheric electron content has been determined from GPS observations alone, using two stations viewing a common ionospheric volume but with very different intersection geometries of the ray paths with the protonospheric flux tubes, as suggested by Bishop et al. (1997).

## Experimental Measurements

Dual frequency observations of GPS satellites have been made at Aberystwyth (52.4°N, 4.1°W) since mid-1996, with processing of the observations to obtain equivalent vertical total electron content using the SCORE procedure. Further information about the SCORE process can be found in Lunt et al. (1998b) and the references therein. It can be noted that for the present study a lower latitude cut-off, for the ionospheric penetration points of the ray paths of observations input to SCORE for calibration purposes, of 0.75 degrees to the south of Aberystwyth was used in accordance with the modelling work of Lunt et al. (1998b). A similar simulation investigation to that described in the earlier paper established that the appropriate cut-off for accurate calibration of the Dartmouth observations was 0.85 degrees to the south of that station.

For a period of several months a second receiver, identical to the first receiver, was also deployed at Aberystwyth It was demonstrated that SCORE yielded TEC measurements from the two systems that were in excellent agreement, even though the unknown biases were very different for the two receivers. Figure 1 shows the differences in the average equivalent vertical TEC measured by the two systems for each day of the test periods. It can be seen that the average TECs obtained from the two receivers agreed in general to a small fraction of a TECU. The error bars represent one standard deviation of the scatter of the individual measurements within each day. It can be noted that the day with the large error bars was one on which one of the receivers did not track all of the satellites in the constellation. Following the comparison trials between the two receivers, the second system was moved to Dartmouth (50.4°N, 3.6°W) in November 1997, for 8 months of independent measurements.

## Model Studies

The modelling work, described by Lunt et al. (1998a), has shown that, because of the geometry of the geomagnetic field, ray paths to the south of stations at European mid-

latitudes were likely to encounter more protonospheric electrons than those to the north. The aim of the present experiment was to test this prediction by comparing observations to the south of Aberystwyth with those to the north of Dartmouth. The ray paths intersected a common volume of ionosphere between the stations, but those from Aberystwyth were likely to have longer paths through flux tubes in the protonosphere with lower L-shells and consequently higher electron densities.

The SUPIM model, described in Lunt et al. (1998a), was used to simulate GPS measurements of total electron content (TEC) at the two stations. The model was run in simulation time for 16 days to represent complete filling of the protonospheric flux tubes from the underlying ionosphere. The resultant electron densities were integrated along ray paths to yield total electron content. Examples of diurnal plots of equivalent vertical TEC obtained from the model are shown in Figure 2, corresponding to conditions in December at solar minimum. These correspond to observations made at Aberystwyth, looking south along a ray path with an ionospheric penetration point (IPP) latitude (at 350km altitude) of 51.4°N, and for Dartmouth looking north with an identical IPP latitude. The solid curve in each plot gives the equivalent vertical TEC integrated along the ray path to GPS altitude, while the dashed curve represents the equivalent vertical TEC on the ionospheric section of the ray below 1100km. Comparison of the dashed curves for the two stations confirms that the ionospheric TEC is essentially identical for the two geometries. The difference between the two curves on each of the plots gives the equivalent vertical TEC for the sector of the ray paths through the protonosphere between 1100km and 20200km. It can be seen that the protonospheric contribution amounts to some 2 TECU (1 TECU $\equiv$ $10^{16}$ electrons $m^{-2}$) regardless of time of day for the Aberystwyth observations, but only about 0.5 TECU for the Dartmouth geometry.

**Experimental Results**

Examples of diurnal plots of equivalent vertical TEC obtained from SCORE processing of observations at Aberystwyth and Dartmouth are shown in Figure 3. The Aberystwyth results refer to measurements for ray paths south of the station with IPPs within a one degree wide latitudinal band centred on 51.4°N. The results from Dartmouth for the same day come from measurements for ray paths north of the station with IPPs within a one degree wide latitudinal band also centred on 51.4°N. The plots are made up from segments corresponding to observations from individual satellites with a data interval of 1 minute. It can be noted that, because of the orbital inclination of the GPS satellite of 55 degrees, measurements to the north from Dartmouth are sparser than those to the south from Aberystwyth. Close examination of the plots in Figure 3 shows that, in general, at any time the Aberystwyth TEC exceeds that for the Dartmouth ray paths. Results from the individual satellite segments at any instant have been averaged to form average diurnal curves for the two sets of observations. Corresponding data points from the two stations have then been differenced and a mean value of this TEC difference obtained for each day. Figure 4 plots this difference in equivalent vertical TEC from the two stations for each of the days on which measurements were available. The error bars again represent one standard deviation about the mean. Figure 4 can be related directly to Figure 1 where the

two receivers were co-located. It can be seen from Figure 4 that for most days the difference is positive, with the measurements for the Aberystwyth geometry exceeding those from Dartmouth in accord with the model predictions. The mean value of all of the differences shown in Figure 4 is 0.7 TECU. While this is less than the 1.5 TECU inferred from the model simulations, it must be recalled that the SUPIM study referred to a full protonosphere after 16 days refilling. In practice, the geomagnetic storms deplete the protonospheric flux tubes on a time scale considerably shorter than 16 days, so that the modelled values may be overestimates of the actual average situation. It can be noted that the highest daily average in Figure 4 is about 2 TECU, and there are many days with values between 1 and 2 TECU. Thus, it can be concluded that there is broad agreement between the model predictions and the experimental results.

## Discussion and Conclusions

Results have been presented from GPS measurements of TEC made at two European mid-latitude stations separated by 2 degrees of latitude. The results demonstrate that a measurable difference can be found in the TEC that can be attributed to differences in the ray path / protonospheric flux tube geometry of the two sets of observations. For the current work the equivalent TEC on ray paths to the south exceeds that on corresponding ray paths to the north by an average of 0.7 TECU. This value is smaller than that predicted by the model. However, it is almost certain that the conditions of the simulation may have resulted in an overestimation, when considered against likely actual behaviour of the protonospheric plasma. The results from this method are in excellent agreement with measured differences of TEC from GPS and NIMS satellites by Lunt et al (1998c), for which the average protonospheric excess TEC was determined to be 0.75 TECU at 51.4°N.

The work reported here has importance to GPS observations, both to measurements of TEC and to the compensation for the effects of TEC on the propagation of the signals. It has been demonstrated that there are small differences in the measured TEC arising from electrons on protonospheric sections of GPS ray paths looking north and south from a mid-latitude European station. The ray paths considered here were at relatively high elevation. However, some uses of GPS involve ray paths of low elevation, where if equatorwards of the station the protonospheric contribution could be large, but negligibly small if poleward. The thin shell models of the ionosphere that are currently used in GPS TEC work clearly fail to replicate the asymmetries introduced by the protonospheric flux tubes. While the absolute magnitude of the protonospheric contribution may be small for the conditions of the present study, nevertheless, for lower elevation rays, stations at lower mid-latitudes and electron densities appropriate to solar maximum, the protonosphere could impose a limitation to accurate determination of ionospheric TEC from GPS observations. Likewise, for these situations the protonosphere could limit the accuracy of models compensating for the effects of TEC on single-frequency GPS

systems. The present study also has implications for global and regional mapping of TEC using GPS signals. If accuracies better than the 5 TECU currently claimed (Mannucci et al., 1998) are to be achieved, then it will be necessary to address the failure of thin shell ionospheric models to describe the asymmetries of the protonosphere. In Mannucci et al. (1998), global ionospheric maps were produced by calculating coefficients for basis functions. This calculation was performed by minimising the residual difference between measurements and predictions made from the maps at the IPP of the measurement. The present study has shown that, for European mid-latitude stations separated by two degrees of latitude, there is a residual difference of some 0.7 TECU in the measurements for common IPPs between the stations. The difference arises because the ray paths from the more northerly station encounter higher protonospheric electron densities than those from the station to the south. Larger differences may occur for greater latitudinal separations of the receivers. It is thus possible that the coefficients for the basis functions for the ionospheric maps will be modulated according to the directions of the measurements used to minimise the residual differences.

*Acknowledgements*

The GPS work at the University of Wales, Aberystwyth has received support from the USAF European Office of Aerospace Research and Development under contract F61708-97-W0129. NL acknowledges the support of a UWA Postgraduate Studentship award. Support by NorthWest Research Associates was provided under contract F19628-97-C-0078.

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Figure 1. Average difference in equivalent vertical TEC measured by two identical receivers co-located at Aberystwyth on selected days, denoted by day numbers in 1997.

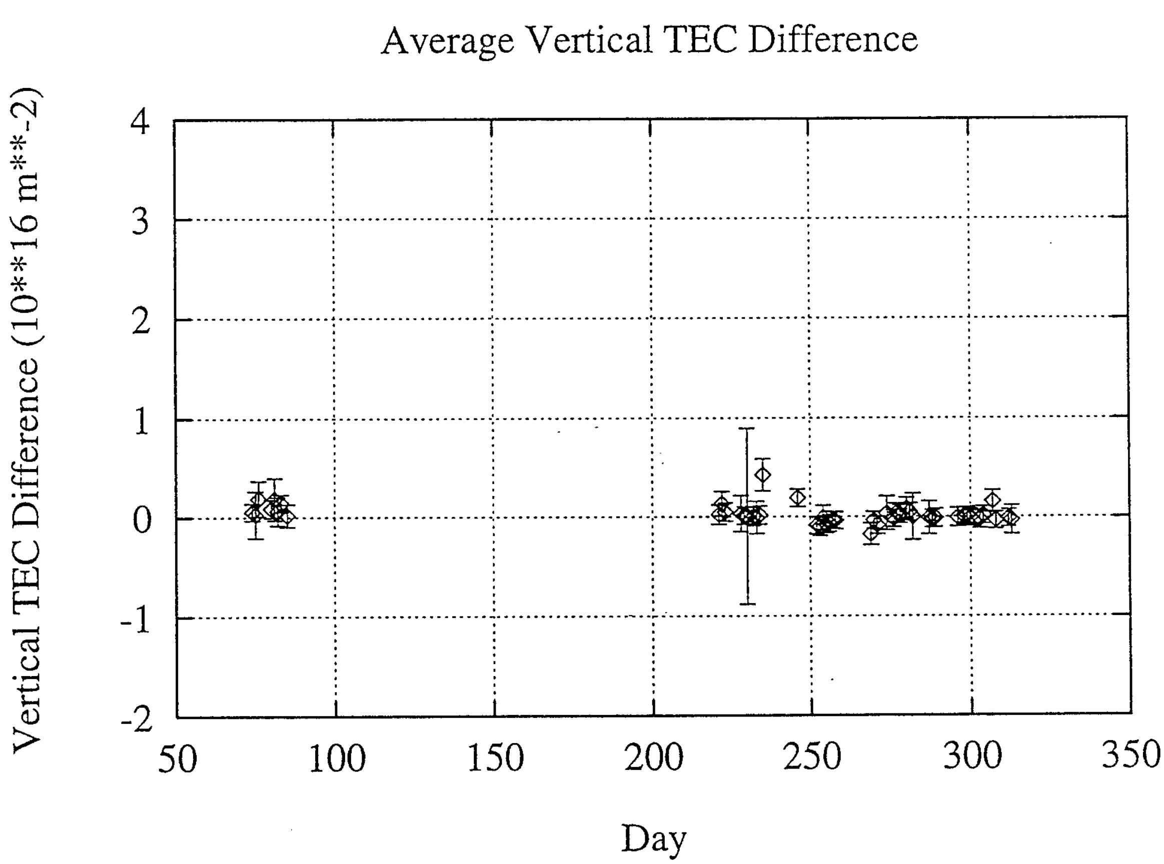
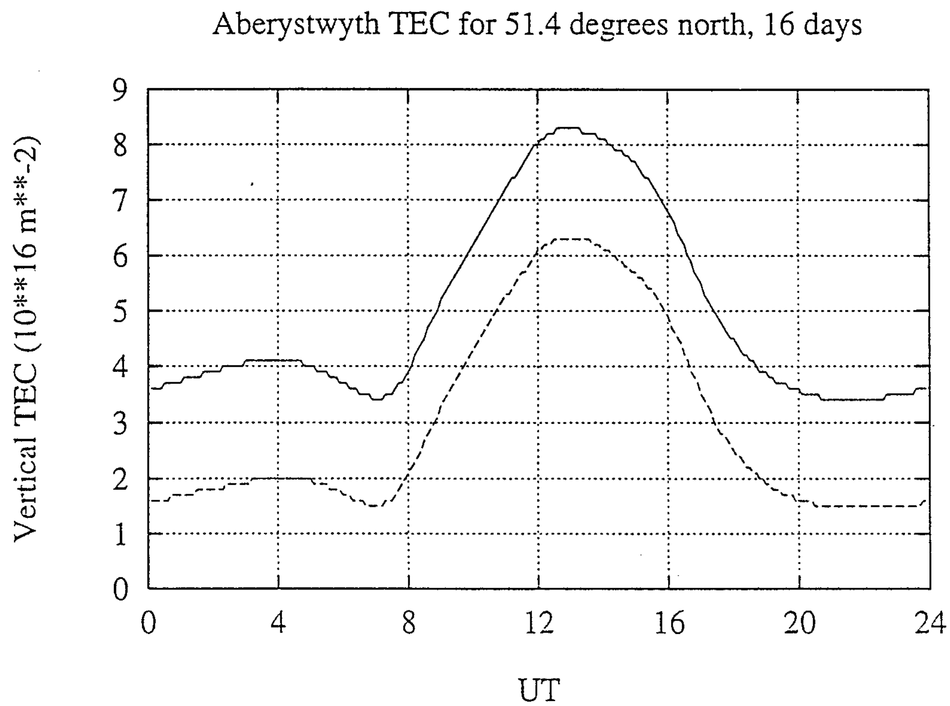


Figure 2. Diurnal plots of equivalent vertical TEC for a ray path with ionospheric penetration point at 51.4°N (a) looking south from Aberystwyth and (b) looking north from Dartmouth. The plots have been obtained by integration of electron densities from the SUPIM model to 1100km altitude (---) and to GPS altitude of 20200km (—).



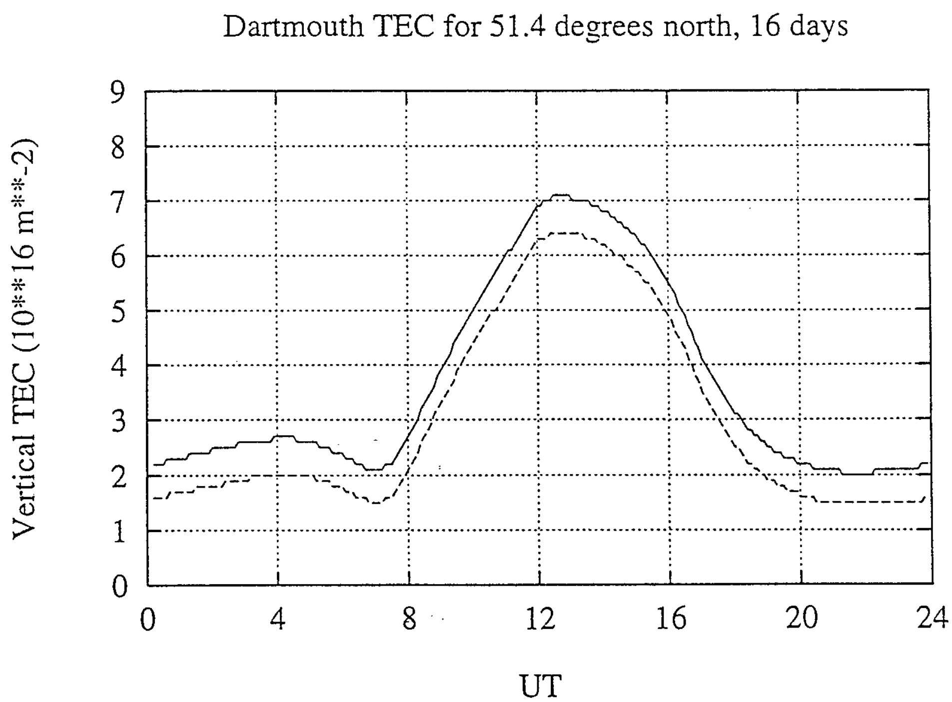
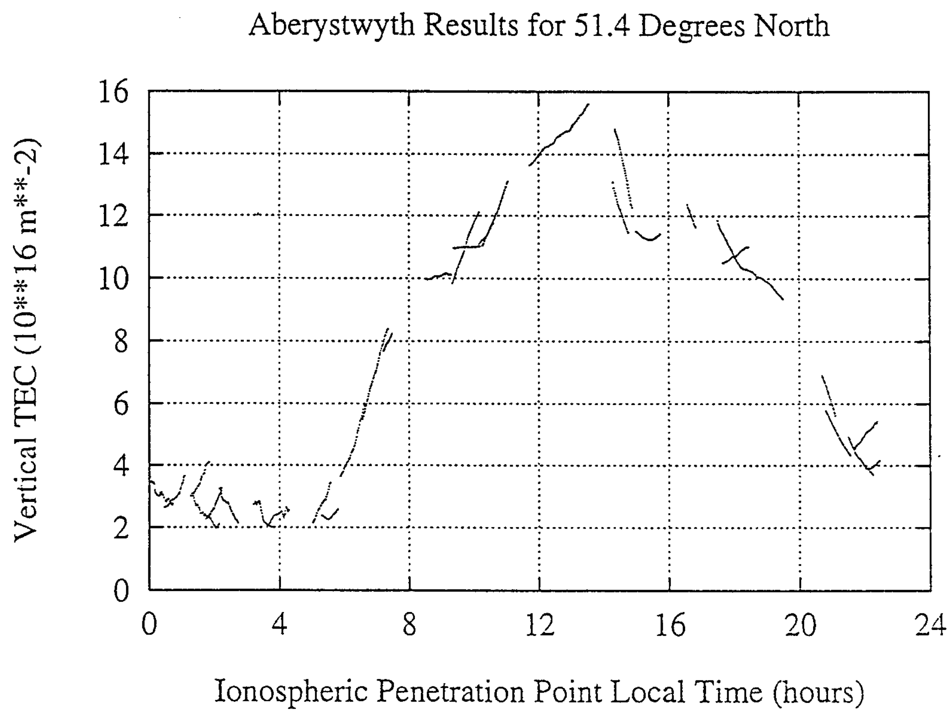



Figure 3. Diurnal variation of equivalent vertical TEC obtained from GPS observations at (a) Aberystwyth and (b) Dartmouth for ray paths with ionospheric penetration points at 350km in a one degree wide latitudinal band centred on 51.4°N.



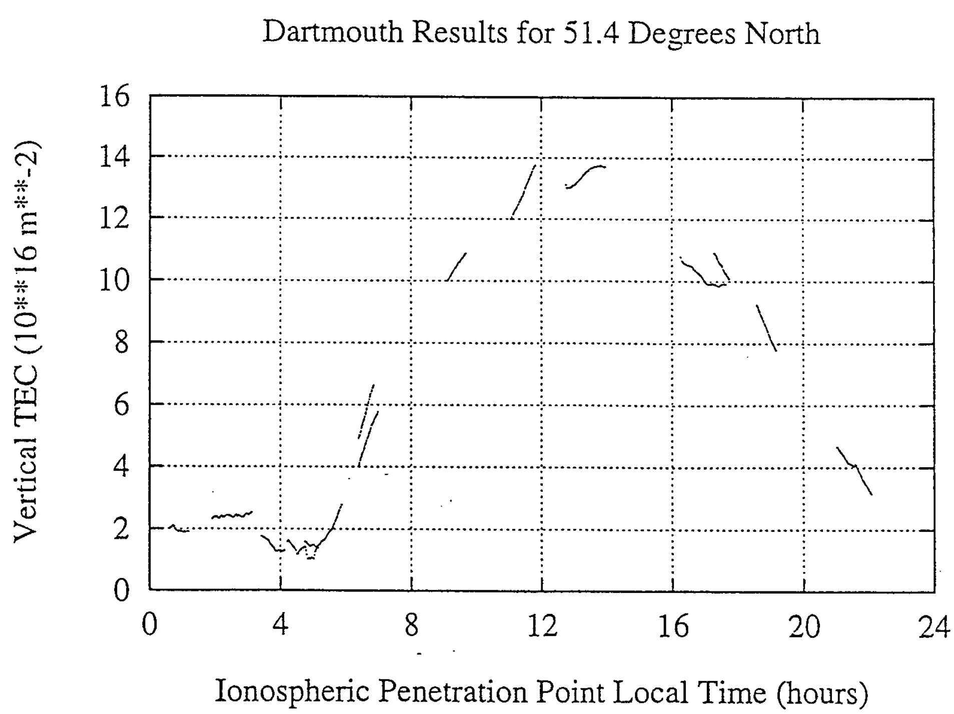
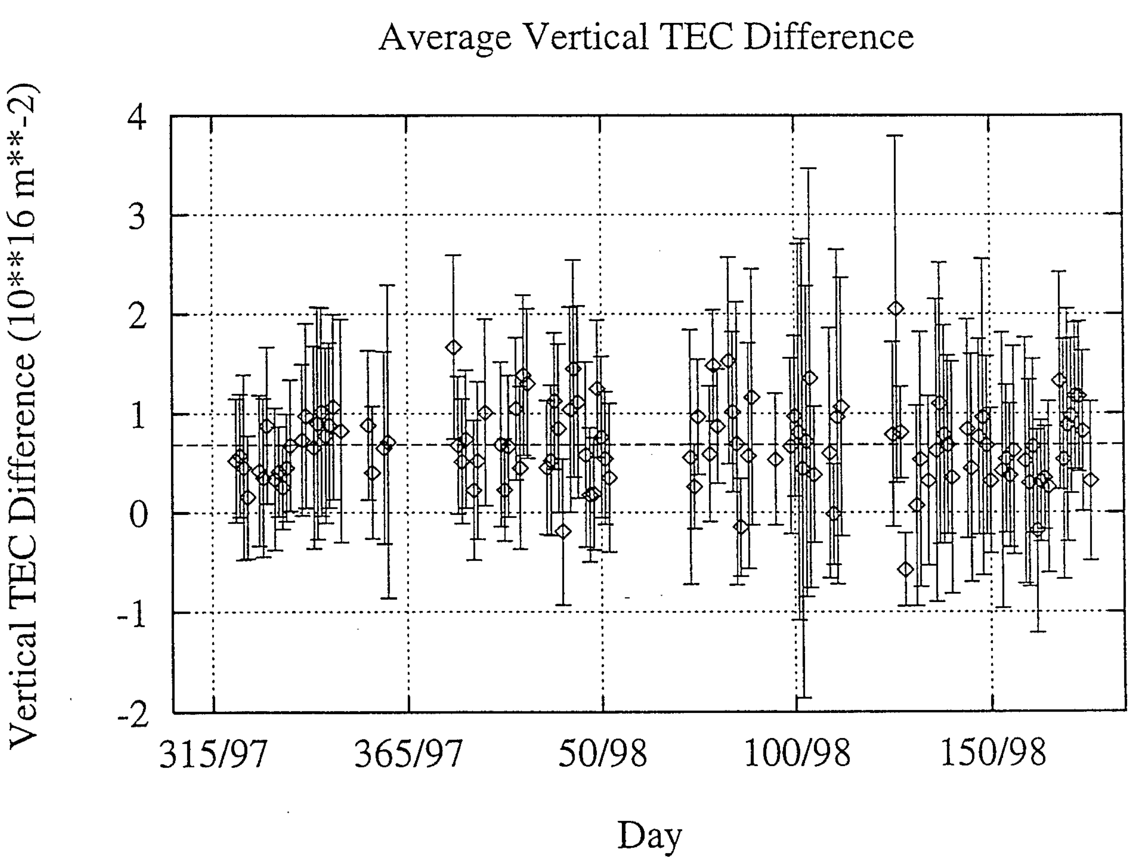



Figure 4. Average difference in equivalent vertical TEC obtained from GPS measurements at Aberystwyth and Dartmouth for ray paths with ionospheric penetration points in a one degree wide latitudinal band centred on 51.4°N for selected days, denoted by day numbers in 1997 and 1998.



**Appendix E** Paper entitled 'A new approach to modelling of the main ionospheric trough over Europe using tomographic images' presented at COST251 Workshop, El Arenosillo, Spain, October 1998 and prepared for inclusion in the Conference Proceedings.

The experimental work directed toward the tomographic imaging of the spatial distribution of ionospheric electron density over UK has received wider support from DERA, Malvern. This further support enabled the establishment of additional receiving stations for the routine monitoring of NIMS satellites so that the chain now spans the latitudinal range of UK from the northern tip of Shetland to the south coast of England. The routine production of tomographic images, covering the interface region between the auroral and mid-latitude ionospheres dominated by the main trough, has enabled an investigation to be made of the characteristics of this feature. A new approach has been taken to the modelling of the trough, a structure that is not well replicated in current ionospheric models. The paper describes the work carried out at Aberystwyth on the development of the trough model using tomographic images and demonstrates the potential for the technique by comparison of results with the limited observations available from ionosondes. The contribution of DERA to the project is recognised by the inclusion of J.A.T. Heaton and P.S. Cannon as authors.

# A new approach to modelling of the main ionospheric trough over Europe using tomographic images

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**Abstract**

Tomography provides a mathematical framework for combining data from many projections to form a two-dimensional image. In the ionospheric application total electron content (TEC) is measured between one of the polar-orbiting Navy Ionospheric Monitoring System (NIMS) satellites and a chain of ground-based receivers. The data set from a satellite pass is inverted in a reconstruction algorithm to create an image of the distribution of electron concentration over a large spatial region.

Five receiving systems have been deployed at Unst (60.8°N), Lossiemouth (57.7°N), Hawick (55.4°N), Aberystwyth (52.4°N) and Dartmouth (50.3°N) since October 1997. The systems automatically record NIMS satellite passes and provide a large number of TEC measurements for the routine production of tomographic images of the ionosphere over western Europe. Observations from ionosondes, located at Chilton (51.5°N, 1.3°W) and Lerwick (60.2°N, 1.2°W), have been incorporated into the tomographic reconstruction to improve the representation of the vertical profile in the resulting images.

Individual images reveal that the main ionospheric trough is located to the north of the UK during nights with quiet geomagnetic conditions. More disturbed conditions allow the trough to be imaged at latitudes directly over UK, while the trough was found as far south as northern France during a period of high Kp. The database of tomographic images has been used to infer statistics about the morphology of the trough and its latitudinal motion throughout the night. This information is then used to extrapolate a single tomographic image zonally, allowing the model to extend some 60 degrees in longitude from mid-Atlantic to eastern Europe. A comparison is made between foF2 values from ionosondes over the European sector and the electron density in the trough region of the model.

## 1.0 Introduction

It is well established that the main or mid-latitude trough is the principal ionospheric structure at mid- and sub-auroral latitudes during nighttime. It has been studied with a variety of instruments and techniques, including ionosondes, TEC and incoherent scatter, as well as satellite-borne experiments. Statistical studies have attempted to define relationships between the latitudinal position of the trough and local time and geomagnetic activity indices (for example, Rycroft and Burnell, 1976). While these approaches have been partially successful, it is still unreliable to use these statistical methods alone to predict the trough position.

The use of ionospheric tomography to study the trough has been a relatively recent addition to the observational techniques (Kersley et al., 1997). A key advantage of ionospheric tomography is the ability to image the electron density over a large region of latitude. When applied to study of the trough, tomography gains a further advantage in not being adversely affected by the low densities in the trough region.

The current paper addresses the mapping of the trough over Europe. A new approach has been taken, where the entire trough model in 3-dimensions is based on a single tomographic image from one longitude. Although the tomography receiver chain is located in UK it has been possible to extrapolate the image to other longitudes covering some 60 degrees centred on UK.

## 2.0 Tomographic imaging

Five tomography receiving systems have been deployed in UK since the autumn of 1997. The receivers, spanning a latitude of more than 10°, are located at Unst (60.8°N, 0.8°W), Lossiemouth (57.7°N, 3.3°W), Hawick (55.4°N, 2.8°W), Aberystwyth (52.4°N, 4.1°W) and Dartmouth (50.3°N, 3.6°W), as shown in the map in Figure 1.

The tomography experiment is designed for routine imaging of the ionosphere using the radio transmissions from the Navy Ionospheric Monitoring System (NIMS). The satellites are in polar orbits at approximately 1100 km and transmit phase-coherent radio signals at 150 and 400 MHz. The signals are used to make differential doppler measurements, from which the relative total electron content is found along many ray paths as the satellite passes from horizon to horizon. The receivers run unattended and monitor all satellite passes above the horizon that are recorded for a duration of longer than two minutes. The sites at Unst and Dartmouth are networked, allowing the phase data to be transferred to Aberystwyth via a phone line and modems.

Absolute TEC is estimated using a multi-station development of the least-squares calibration method described by Leitinger et al. (1975). Compensation for the longitude difference between the satellite and the receiver is made using a cosine correction at the zenith angle of the ray path at 350 km altitude during nighttime and 280 km during the day.

The tomographic images have been reconstructed using the method described by Fremouw et al. (1992), with an orthogonal basis set of functions formed from a range of Chapman profiles, with a linear gradient in the scale height of the topside ionosphere. This procedure is used to create an image of the large-scale features in the ionosphere, with subsequent processing by means of an Algebraic Reconstruction Technique (ART) algorithm to reconstruct the smaller-scale structures in the tomographic images. Ionosondes at Chilton (51.5°N,1.3°W) and Lerwick (60.2°N,1.2°W) make routine measurements of plasma frequency of the ionosphere at intervals of 30 minutes and these have been inverted using the POLAN procedure. Where available, ionosonde measurements within 15 minutes of a satellite pass have been incorporated into the tomographic inversion to improve the reconstruction of the vertical profile of the bottomside ionosphere.

## 3.0 Mapping the mid-latitude trough

The model was based on a tomographic image over UK at the time of the satellite pass, with the latitudinal size of the pixels being about 30 km. This was taken to give the best representation of the ionospheric electron density at 0° longitude at the time of the pass. The image was then extended in longitude to ± 7.5°,15°, 22.5° and 30° in the following manner. The zonal gradient in electron density was obtained by running the PIM model (Daniell et al., 1995) on the same grid as the tomographic image at 0° longitude and at a second longitude from those listed. The ratio of the electron density in each pixel predicted by the PIM model at the two longitudes was then applied to the tomographic image to provide the zonal gradient in electron density. If the electron density in the ionosphere represented by the PIM model is defined by

$$P_{ijk},$$

where $i$=latitude pixel index, $j$=height pixel index and $k$=longitude pixel index,

and the electron density in the tomographic image is defined as

$$E_{ijk},$$

where $k$=0=index for longitude 0°,

then at any different longitude the actual electron density was taken to be

$$E_{ijk} = E_{ij0} \times P_{ijk}/P_{ij0}\,.$$

While the above procedure allowed for longitudinal gradients, additional steps were needed to simulate the latitudinal motion of the tough with local time. The tomographic image was moved north or south, according to the expected movement of the trough over the local time corresponding to the longitude offset required, e.g. 7.5°E corresponds to +30 minutes. The

expected movement at the particular time of the image was obtained essentially from the statistical behaviour of the trough shown in Figure 2. The average positions of the trough minimum and the range presented in the figure have been compiled from all of the tomographic images showing troughs during the present experiment. If the image has to be moved south by a number of pixel represented by the integer $n$, then

$$E_{ijk} = E_{(i+n)j0} \times P_{ijk}/P_{ij0}.$$

A further consideration to the longitudinal mapping of the trough position is the geomagnetic field, since the trough is aligned geomagnetically. The International Geomagnetic Reference Field (IGRF) model was run to map the trough along geomagnetic coordinates to a different geographic longitude. If the image must be moved south due to the geomagnetic field by a number of pixels represented by the integer $m$, then the final electron density is given by

$$E_{ijk} = E_{(i+n+m)j0} \times P_{ijk}/P_{ij0}.$$

## 4.0 Results

Figures 3 to 8 show six tomographic images, that were taken to be representative for the mapping of the trough over Europe. It can be seen that in each of the chosen images the mid-latitude trough is the dominant feature. The six images represent a range of geomagnetic conditions and times. Of particular interest is the narrow trough with the steep poleward wall shown in Figure 4. The most southerly location for the trough during the entire period of the observations was that presented in Figure 7. This image, obtained from a satellite pass at about 02:59 UT on 23 November 1997 shows the trough minimum at 49°N.

An example of a map of NmF2 obtained by the technique is shown in Figure 9. It covers the region from 40 to 70°N and 30°W to 30°E (geographic coordinates) and was created from the tomographic image at 18:51 UT on 27 March 1998 presented in Figure 3. It can be seen that the latitude of the trough minimum lies further to the north as the longitude increases to the east, following the inclination of the L-shells. Ionosonde values of foF2, and hence NmF2, were available from Kiruna, Lycksele, Rugen and St. Petersburg were at 19:00 UT and are shown in Table 1. It can be seen that in most cases there is reasonable agreement between the predictions of the map and the independent measurements. Figure 10 shows the map of NmF2 at about 20:10 UT on 1 March 1998, a case where the trough was narrow in latitude with a steep poleward wall. The three ionosondes, at Uppsala, Rugen and St Petersburg, provided NmF2 comparisons at 20:00 UT, again showing reasonable agreement (Table 1). Less than one hour later at 21:57 UT, the trough was some 4° further south and the poleward wall less steep (Figure 11). The ionosonde at Rugen, in the vicinity of the equatorward gradient again providing a reasonable comparison for the electron density at the F2-layer peak.

Figure 12 shows the NmF2 at 21:29 UT on 4 March 1998. The ionosondes at Rugen and St Petersburg had measurements at 21:00 and 22:00 UT that have been interpolated to comparison with the trough map (Table 1). Figure 13 shows the NmF2 map for the case where the trough is at its extreme southward position of 49°N at 02:59 UT on 23 November 1997. During these disturbed conditions (Kp 7+), the ionosonde at Rugen confirms the density on the poleward wall of the trough while to the south of the trough minimum, Rome and Sofia provide comparisons.

Figure 14 is of interest as it represents a time in the early morning when there is an increase in electron density both to the east of the UK due to sunrise and to the west from the regular nighttime gradient. The values available from the two ionosondes at Uppsala and St. Petersburg do not compare well with the NmF2 maps (see Table 1). However, it can be seen that these stations are in the vicinity of the steep gradient on the equatorward wall of the trough, where a small error in the latitudinal position of the trough will result in a large error in electron density. In addition, the zonal gradient obtained from the PIM model may not be accurate at this time.

Figure 15 shows the comparison of the NmF2 predicted from the maps with ionosonde data for the cases shown here. It can be seen that the densities from the ionosondes in the region of the trough compare reasonably well with those estimated by the modelling procedure.

| Date | Time (UT) | Site | Ionosonde NmF2 | Model NmF2 |
|---|---|---|---|---|
| 5 November 97 | 05:12 | Uppsala | 0.6 | 0.9 |
| | | St. Petersburg | 0.8 | 1.6 |
| 23 November 97 | 02:59 | Rugen | 0.5 | 0.6 |
| | | Rome | 2.1 | 1.9 |
| | | Sofia | 2.1 | 1.6 |
| 1 March 98 | 20:10 | Rugen | 1.0 | 1.0 |
| | | Uppsala | 0.7 | 0.6 |
| | | St. Petersburg | 0.5 | 0.4 |
| | 21:57 | Rugen | 1.0 | 0.8 |
| 4 March 98 | 21:29 | Rugen | 1.3 | 1.6 |
| | | St. Petersburg | 0.5 | 0.4 |
| 27 March 98 | 18:51 | Kiruna | 1.0 | 1.6 |
| | | Lycksele | 2.1 | 2.1 |
| | | Uppsala | 2.8 | 2.8 |
| | | Rugen | 4.0 | 3.2 |
| | | St.Petersburg | 2.1 | 2.1 |

Table 1. Values of NmF2 ($x10^{11}$ electrons $m^{-3}$) from ionosondes located close to the trough and NmF2 from the trough model.

## 5.0 Discussion and conclusions

Tomographic images have been presented that show the mid-latitude trough with a minimum between 65°N and 49°N for various local times and a range of geomagnetic conditions. A new approach to modelling the trough has been demonstrated. The method is based on an actual tomographic image of the ionosphere over UK that is extrapolated to other longitudes using certain criteria. Temporal variation of the trough position has been defined by the average movement of the trough minimum with time found from a database of tomographic images created during winter 1997-1998. In addition, constant geomagnetic latitude co-ordinates were used to map the trough position to another geographic longitude, while the zonal gradient in electron density was obtained from the PIM model. Initial results from the mapping are shown to compare well with observations from ionosondes located from 12 to 30° east of the tomography receiver chain.

Further work is required to improve and validate the trough model. In particular, it will be interesting to compare the full bottomside profile of electron density in the map with inverted real height profiles from the ionosondes. More observations are needed to refine the mapping process for certain time sectors and possibly different seasons and for cases where the gradients on the trough walls are changing with longitude. It can be noted that it is a simple procedure to integrate the electron densities vertically to obtain maps of TEC that could be compared to the predictions of TEC models for the European sector.


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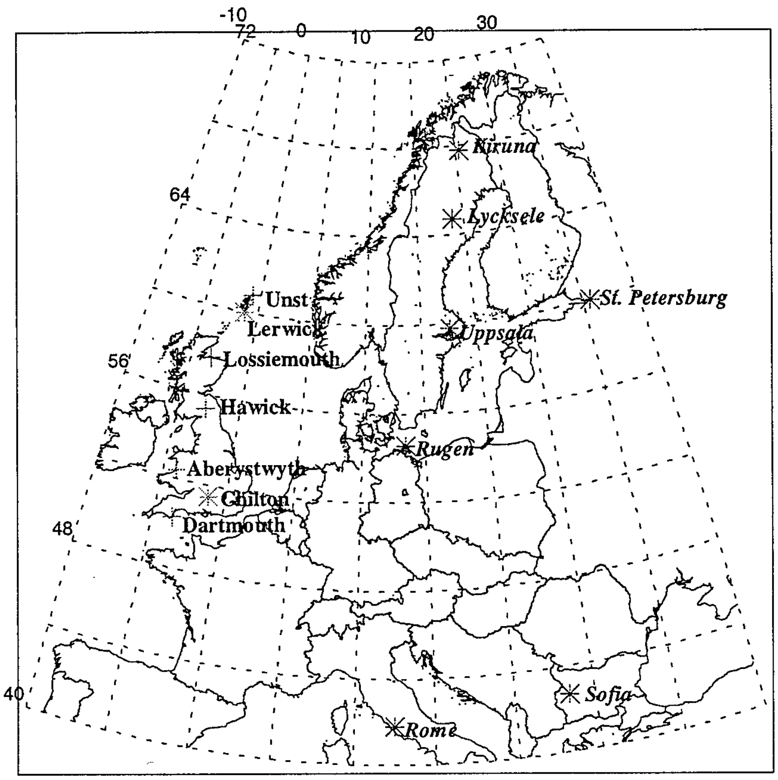


Figure 1. Map showing the locations of the tomography receivers (+) and ionosondes (*). The ionosondes used in the tomography are labelled with **plain bold text** and those used for independent comparison with the model are labelled with *italics*.

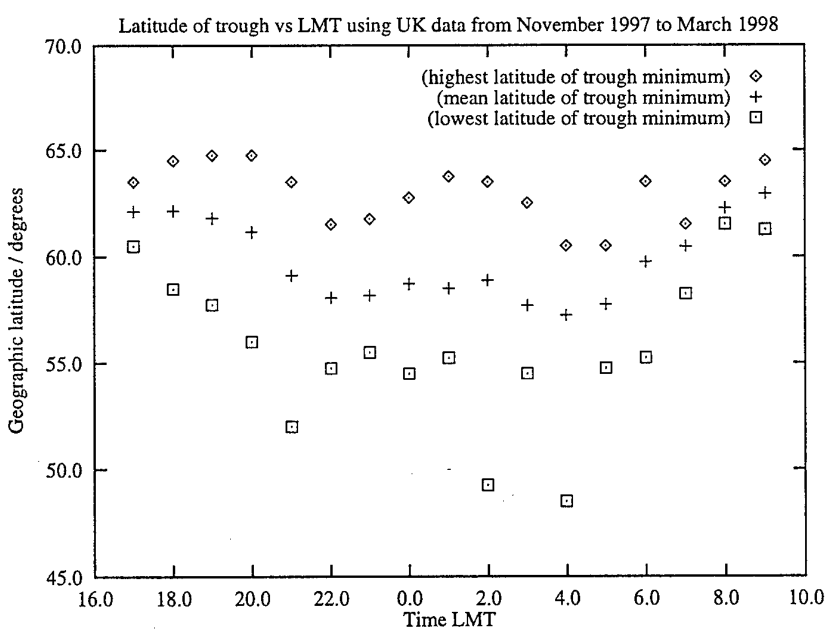


Figure 2. The mean latitudinal position of the trough, as a function of mean local time (MLT), defined as the first turning point in the electron density from the south of the image.

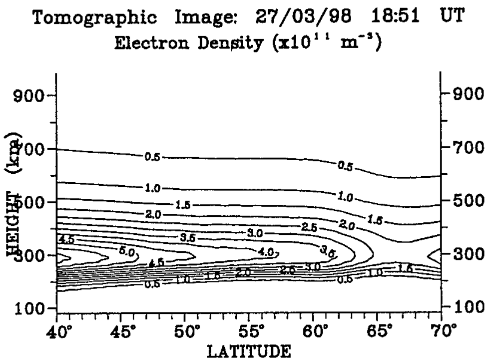


Figure 3. Tomographic image for the satellite pass crossing 55°N at 18:51 UT on 27 March 1998.

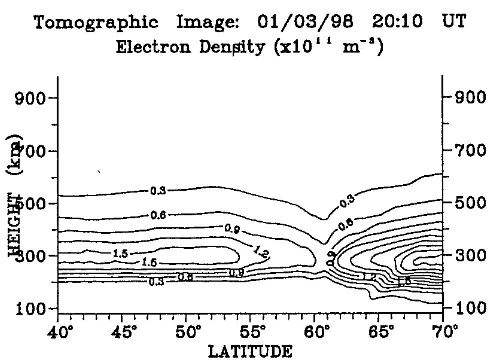


Figure 4. Tomographic image for the satellite pass crossing 55°N at 20:10 UT on 1 March 1998.

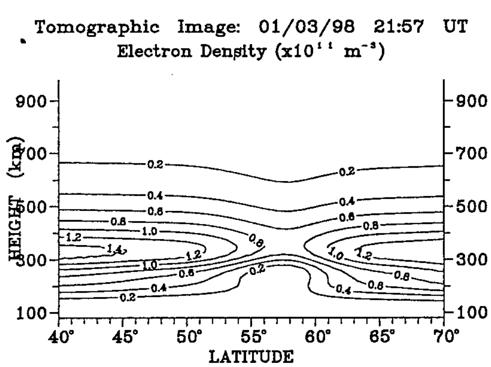


Figure 5. Tomographic image for the satellite pass crossing 55°N at 21:57 UT on 1 March 1998.

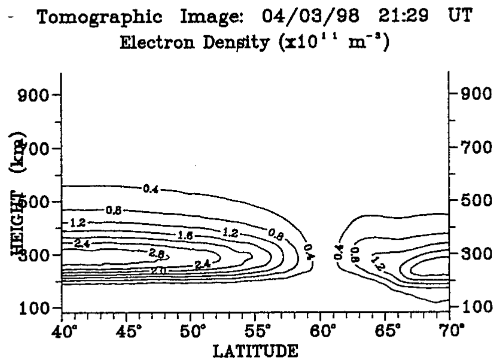


Figure 6. Tomographic image for the satellite pass crossing 55°N at 21:29 UT on 4 March 1998.

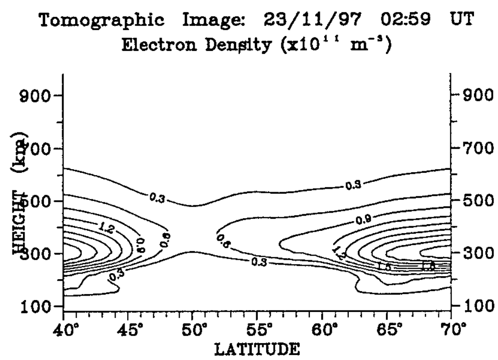


Figure 7. Tomographic image for the satellite pass crossing 55°N at 02:59 UT on 23 November 1997.

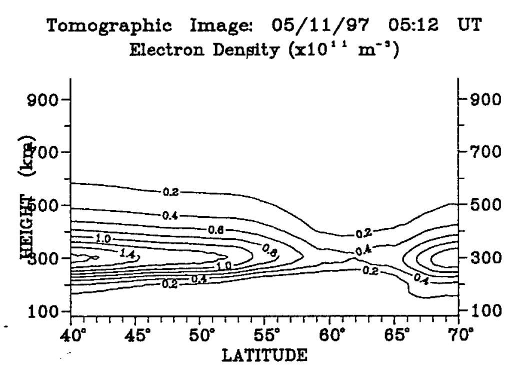


Figure 8. Tomographic image for the satellite pass crossing 55°N at 05:12 UT on 5 November 1998.

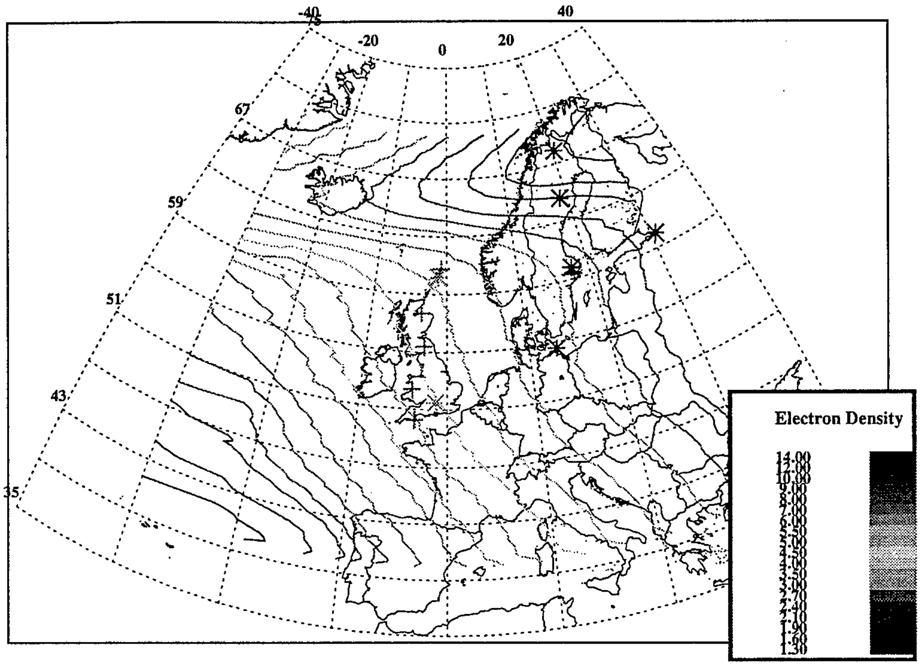


Figure 9. Model of NmF2 over Europe using the tomographic image from a satellite pass at 18:51 UT on 27 March 1998. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark).

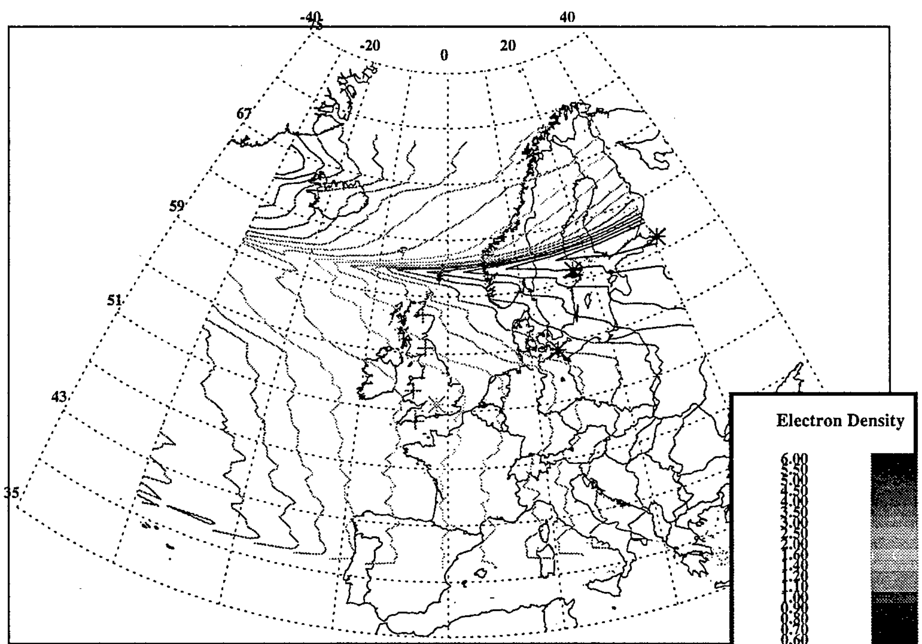


Figure 10 . Model of NmF2 over Europe using the tomographic image from a satellite pass at 20:10 UT on 1 March 1998. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark).

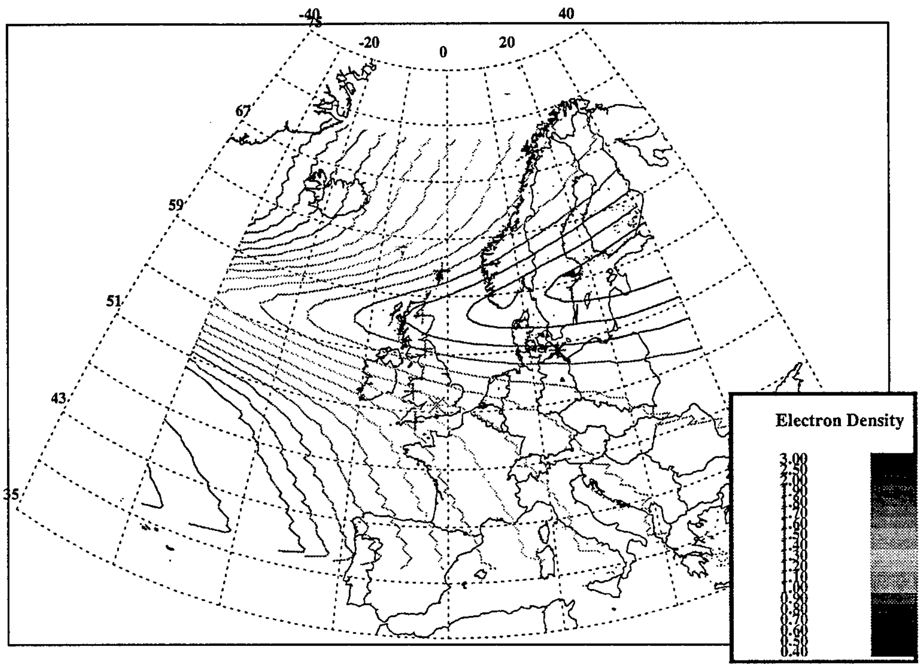


Figure 11. Model of NmF2 over Europe using the tomographic image from a satellite pass at 21:57 UT on 1 March 1998. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark).

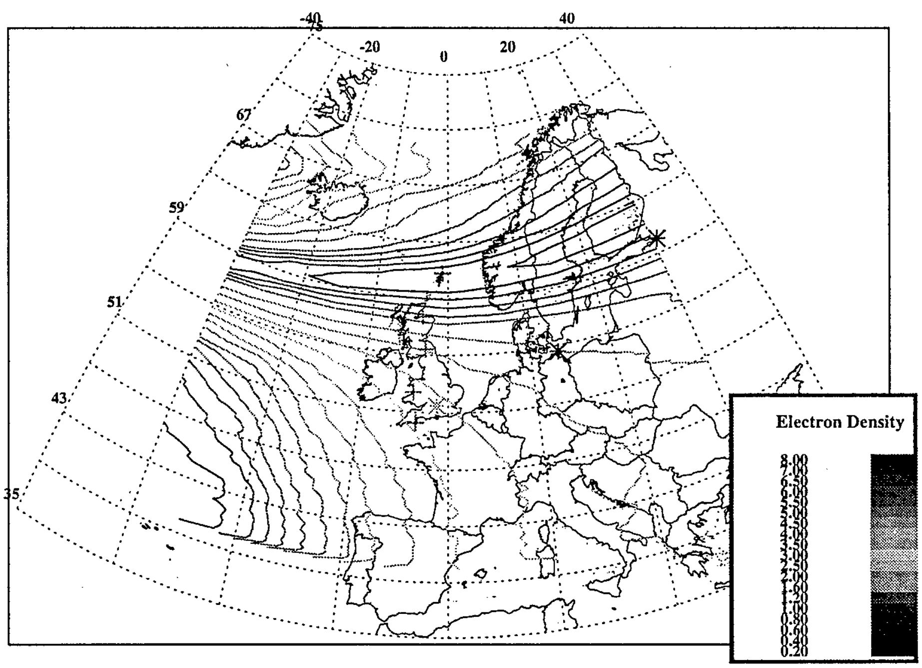


Figure 12. Model of NmF2 over Europe using the tomographic image from a satellite pass at 21:29 UT on 4 March 1998. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark).

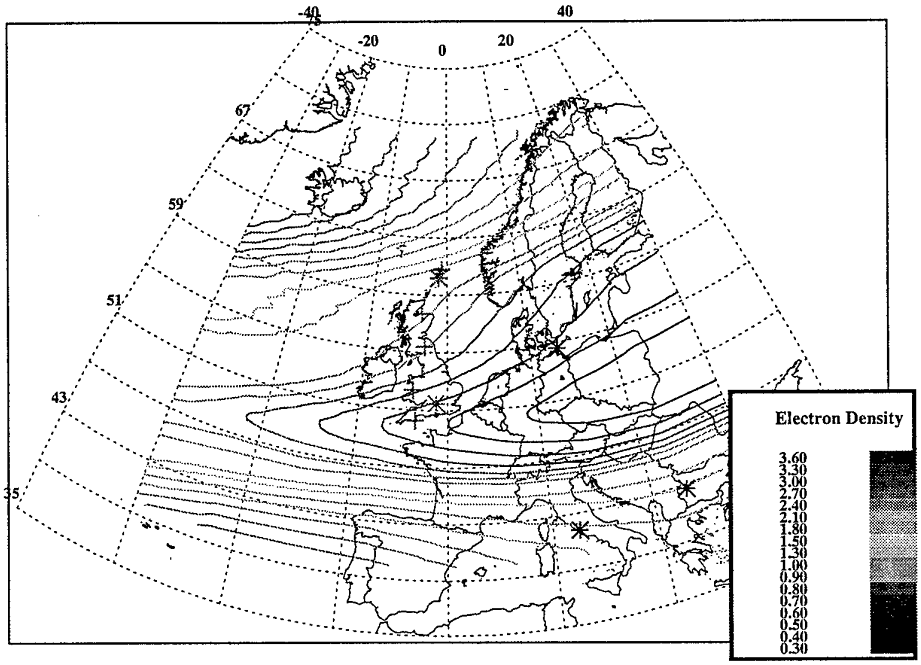


Figure 13. Model of NmF2 over Europe using the tomographic image from a satellite pass at 02:59 UT on 23 November 1997. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark).

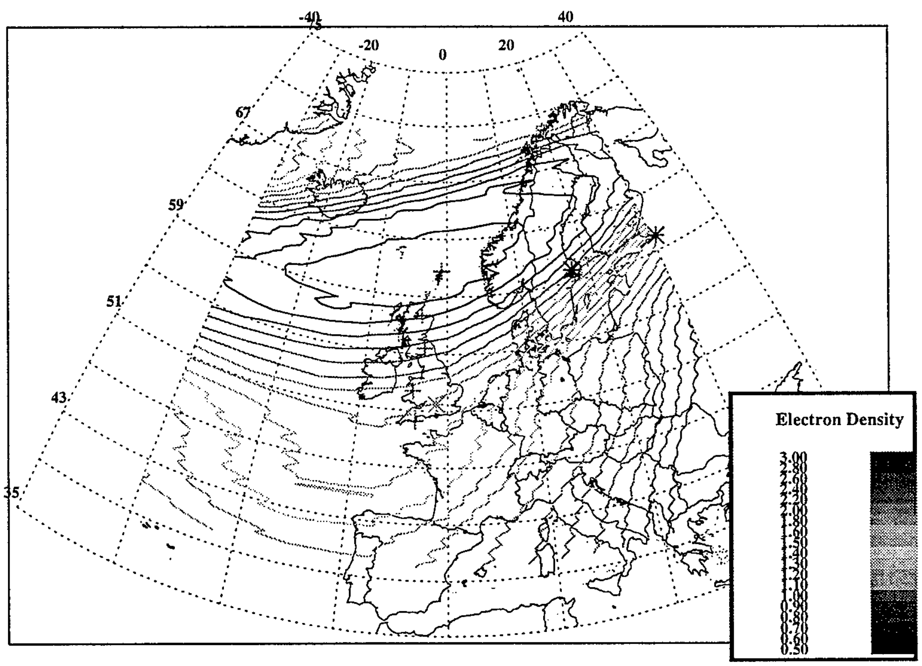


Figure 14 . Model of NmF2 over Europe using the tomographic image from a satellite pass at 05:12 UT on 5 November 1997. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark).

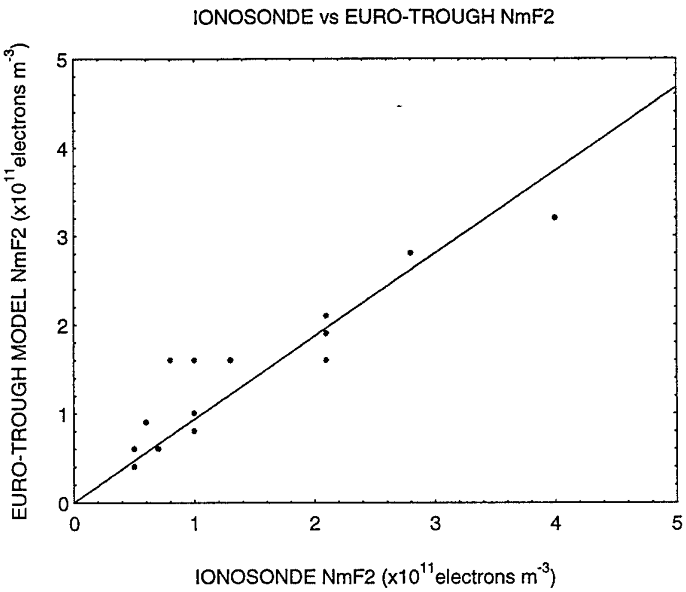


Figure 15. Comparison between the ionosondes and the trough model over Europe for the six maps of NmF2 shown in Figures 3 to 8.

**Appendix F** Paper entitled 'The role of radio tomography in monitoring the near-Earth space environment' presented at European Space Agency Symposium on Space Weather, Noordwijk, Netherlands, November 1998 and prepared for inclusion in the Symposium Proceedings.

The paper outlines the radio tomographic work, shows examples of reconstructed images of ionospheric electron density and a result from the though model. The contribution of DERA, Malvern to the project is recognised by the inclusion of P. S. Cannon in the list of authors.

# THE ROLE OF RADIO TOMOGRAPHY IN MONITORING THE NEAR-EARTH SPACE ENVIRONMENT

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ABSTRACT

Radio tomography offers a new framework for producing images of space plasma at altitudes of hundreds of kilometres above the Earth's surface. The mathematical technique, so successful in the medical field, has shown itself to be applicable to geophysical imaging. In the space-plasma application radio signals from polar-orbiting satellites are monitored at a chain of ground-based receivers to measure the ray path total electron content. The resultant data set is then inverted in a reconstruction algorithm to create an image in two dimensions of structures in the plasma concentration. Following extensive testing and verification using incoherent scatter radar the technique has matured in recent years from being essentially a research tool to providing a new experimental method for monitoring the near-Earth space plasma over wide regions.
The paper describes observations using two experimental systems operated by the University of Wales, Aberystwyth. The deployment in 1997 of a chain of five receiving systems, spanning more than 10 degrees latitude from the Shetlands Islands to the south of England, is now allowing routine production of tomographic images of the mid-latitude ionosphere and its important interface to the auroral region. Results are presented that demonstrate the extreme variability of the plasma in this sector, with structures usually associated with the auroral zone being found over UK under disturbed geomagnetic conditions. The images are being used to develop a model of the main trough that forms such an important feature in the night-time ionosphere in this sector and which is poorly represented in existing ionospheric models used for propagation applications.
A second set of four receivers is located to the north of Scandinavia at Tromsø, Bjørnøya, Longyearbyen and Ny Ålesund. The images reveal the ionospheric signatures of processes originating in the magnetosphere and linked to changes in the orientation of the interplanetary magnetic field. Results are presented showing structures in the plasma at polar latitudes that relate directly to solar-terrestrial coupling mechanisms, vital to the understanding of the effects of space weather. It is demonstrated that radio tomography provides a powerful new method for the routine monitoring of the near-Earth space-plasma environment that has applications to both navigation and communications from satellite-based radio systems.

## 1.0 INTRODUCTION

The use of the technique of radio tomography to monitor the near-earth space environment is a relatively new tool. The ability to image the electron density over large regions using a relatively small number of receivers has proven to be an attractive proposition. After extensive development and verification of the tomographic inversion technique with the European Incoherent Scatter (EISCAT) radar used as an independent instrument for comparison studies (Refs. 1 and 2), it has recently become possible to use the tomographic technique to study the physical processes responsible for the structuring of the ionosphere.
Routine monitoring of the ionosphere over UK and northern Scandinavia is currently in progress using a number of tomographic receivers. The variability of the ionosphere over UK is evident in the present work. In particular, tomography is ideally suited to studying the trough due to both its ability to image the ionosphere over a large region of latitude and it not being adversely affected by the low electron densities found in the trough region. The current work is concerned with mapping the trough over the European region. The tomography receiver chain in UK has been used to create a trough model in three dimensions covering 60° longitude, centred on UK.
The receivers located in northern Scandinavia are ideally placed to investigate the ionospheric signatures of processes originating in the magnetosphere. They also provide a latitudinally extended image of electron density, which can be used in conjunction with measurements from the EISCAT Svalbard radar. The ionospheric signatures of magnetopause reconnection are demonstrated here. Further tomographic studies in the polar cap have focussed on the identification of the cusp and post-noon auroral arcs.

## 2.0 TOMOGRAPHIC IMAGING

Two separate chains of tomography receivers are currently being operated. The UK-based receivers have been deployed since the autumn of 1997. These five receivers span a latitude of more than 10 degrees and are located at Unst (60.8°N, 0.8°W), Lossiemouth (57.7°N, 3.3°W), Hawick (55.4°N, 2.8°W), Aberystwyth (52.4°N, 4.0°W) and Dartmouth (50.3°N, 3.6°W). The Scandinavian chain of receivers are located at Ny Ålesund (78.9°N, 12.0°E), Longyearbyen (78.2°N, 15.3°E), Bjørnøya (74.5°N, 19.0°E) and Tromsø (69.8°N, 19.0°E) and have been deployed since August 1996. The locations of the receiving systems are shown on the map of Figure 1.
The tomography experiment is designed for the routine imaging of the ionosphere using radio transmissions from the Navy Ionospheric Monitoring System (NIMS) satellites. These are in polar orbits at approximately 1100 km altitude and transmit phase-coherent radio signals on 150 and 400 MHz. As a satellite orbits from horizon-to-horizon the received signals are used to make differential-doppler measurements along a large number of intersecting ray paths (Figure 2) that subsequently are used to obtain estimates of relative total electron content (TEC). The receivers run unattended and monitor all satellite passes above the horizon that are recorded for a duration of longer than two minutes. Most of the sites are networked to Aberystwyth, allowing real-time data transfer.
Absolute TEC is estimated using a multi-station development of the least-squares calibration method of Leitinger et al. 1975 (Ref. 3). Compensation for the longitude difference between the satellite and receiver is made with a cosine correction at the zenith angle of the ray path at the mean ionospheric height.

The tomographic images have been reconstructed using the method described by Fremouw et al. 1992 (Ref. 4), with an orthogonal basis set of function formed from a range of Chapman profiles with a linear gradient in the scale height of the topside ionosphere. Subsequent processing by means of an Algebraic Reconstruction Technique (ART) algorithm was used to reconstruct the smaller-scale structures in the images. For the tomography from the UK stations measurements from the ionosondes at Chilton (51.5°N, 1.3°W) and Lerwick (60.2°N, 1.2°W) have been used to improve the reconstruction of the vertical profile of the bottomside ionosphere.

## 3.0 RESULTS

### 3.1 MAIN TROUGH

The tomographic image of Figure 3 was obtained from a satellite pass crossing 55° N at 02:59 UT on 23 November 1997. During this sustained period of disturbed geomagnetic activity (Kp=7+ between 00-03 UT) the trough minimum was seen to the south of the UK. This was the furthest south that the trough was imaged during the period of the UK observations.

A model or mapping procedure has been developed to represent the main trough over the European region. A single tomographic image was taken to give the best representation of the ionosphere at 0° longitude at the time of a satellite pass. The image was then extended in longitude in the following manner. The zonal gradient in electron density was obtained from the PIM model (Ref. 5) on the same grid as the tomographic image at the same longitude as the image and also at a second longitude. The ratio of the electron density in each pixel determined from the PIM model at the two longitudes was then applied to the densities in the tomographic image. While this accounted for longitude gradients, it was also necessary to account for the latitudinal motion of the trough with local time. The tomographic image was moved north or south according to the expected movement of the trough over the local time corresponding to the longitude offset required. The expected movement of the trough was obtained from statistics based on the tomographic images from UK during the present experiment. The final consideration was the alignment of the trough along the geomagnetic field, with the International Geomagnetic Reference Field (IGRF) model being used to map the trough to a different geographic longitude.

Figure 4 shows a tomographic image from a satellite pass crossing 55°N at 21:29 UT on 4 March 1998. It is clearly evident that the main trough, marking the boundary between the mid-latitude and auroral ionospheres is present at 60°N. An example of a map of F-region peak electron density, obtained by the technique described above, is shown in Figure 5. Estimates of foF2 obtained from ionosondes at Rugen ($1.6x10^{11}m^{-3}$) and St Petersburg ($0.5x10^{11}m^{-3}$) have been used to confirm the electron densities in the vicinity of the trough.

### 3.3 MAGNETIC RECONNECTION

The tomographic image of Figure 6 was obtained from measurements made at the high-latitude chain for a satellite pass that crossed 78°N at 10:46 UT on 14 December 1996. The contours seen in the northern part of the image between 77 and 79 degrees reveal three enhancements in the electron density in the F-region with the altitude of the features increasing towards the north. Also present in the image are an enhancement in the E-region, just equatorward of the F-layer enhancements and a filed -aligned enhancement in the density of the topside ionosphere.

By comparing this tomographic image with optical data (Ref. 6) it has been possible to relate these ionospheric features to magnetospheric events. The interplanetary magnetic field was southwards at this time and established signatures of magnetopause reconnection at low latitudes were evident in the optical observations (Ref. 6). It has been postulated that the gradient in the height of the F-layer peak density is caused by soft ion dispersion from the velocity filter effect, though it can be noted that the modelling work of Davis and Lockwood (Ref. 7) resulted in a temporal gradient in the peak height from only electrons. Optical studies have also shown that aurora related to the electron trapping boundary at the poleward edge of the central plasma sheet are found equatorward of the red-dominated low -latitude boundary layer aurora. Consequently, it is reasonable to interpret the E-region enhancement in the tomographic image at 77°N as scattered ring-current electrons on closed field lines, allowing the identification of the open-closed field line boundary as shown by the dotted line in Figure 6. The enhancement extending into the topside ionosphere may represent the signature of a field-aligned current.

## 4.0 SUMMARY

Routine tomographic imaging of the ionosphere over UK has been shown to reveal information about temporal behaviour and the morphology of the main trough, which relates directly to the magnetospheric plasmapause. In addition a mapping procedure has been presented which allows a model of the main trough extending over 60° longitude to be created from a single tomographic image.

Signatures of dayside magnetopause reconnection have been identified in a tomographic image over Svalbard. The ionospheric processes are directly linked to the changes in the orientation of the interplanetary magnetic field. Tomographic imaging has a key role to play in monitoring the ionosphere and consequently in understanding the effects of space-weather.

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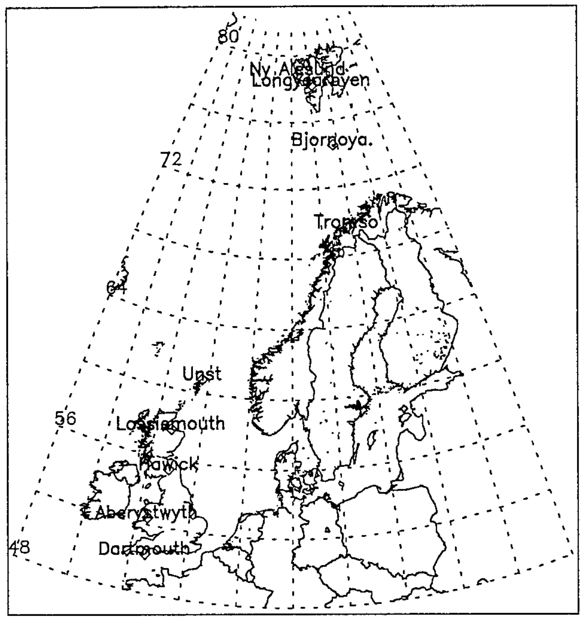


Figure 1. Map showing the locations of the tomographic receiving systems in UK and Scandinavia.

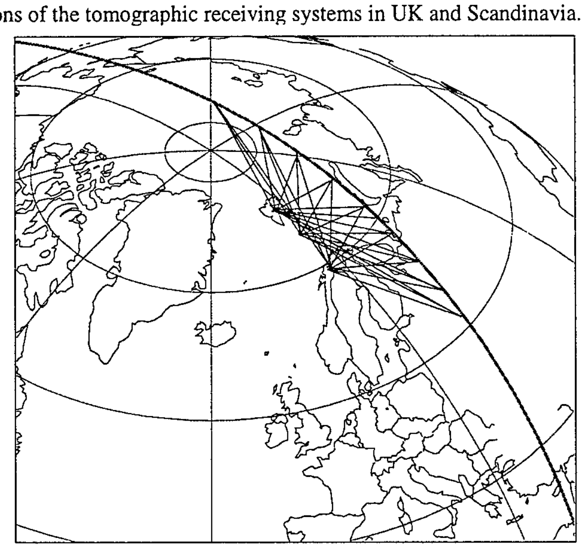

Figure 2. Diagram showing the satellite orbit and a small number of the ray-paths between the satellite and receivers.

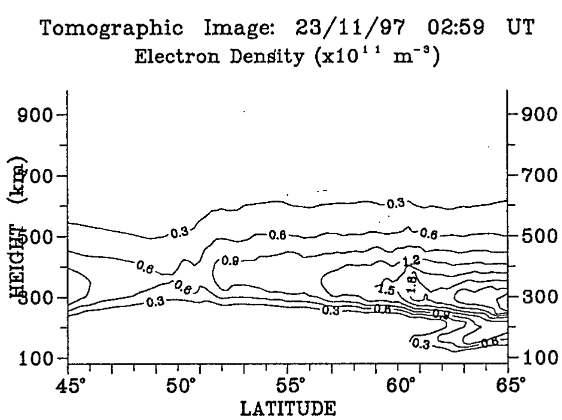


Figure 3. Tomographic image over UK for the satellite pass crossing 55°N at 02:59 UT on 23 November 1997.

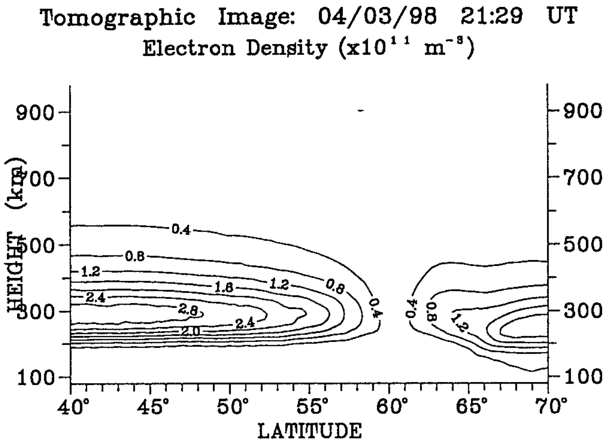


Figure 4. Tomographic image over UK for the satellite pass crossing 55°N at 21:29 UT on 4 March 1998.

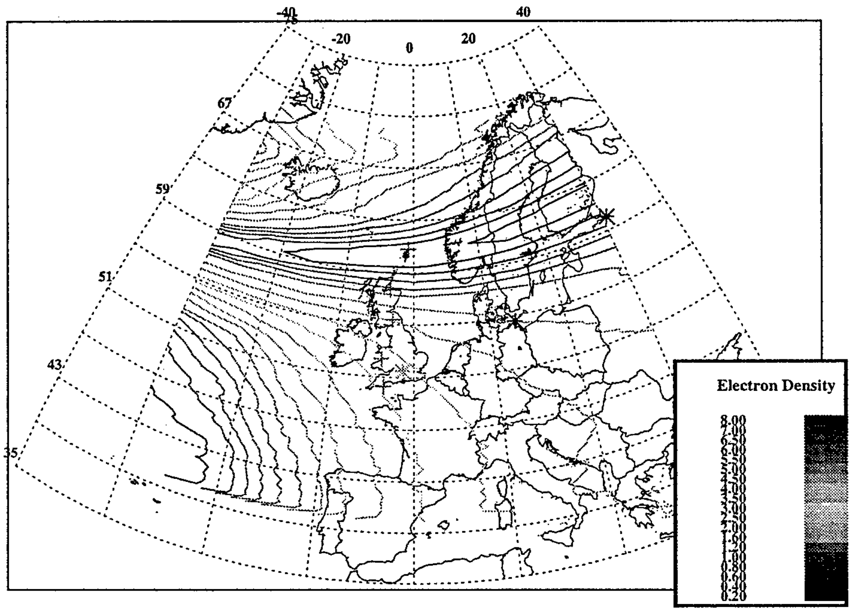


Figure 5. Model of NmF2 over Europe using the tomographic image from a satellite pass at 21:29 UT on 4 March 1998. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark). The electron density is in units of $10^{11}m^{-3}$.

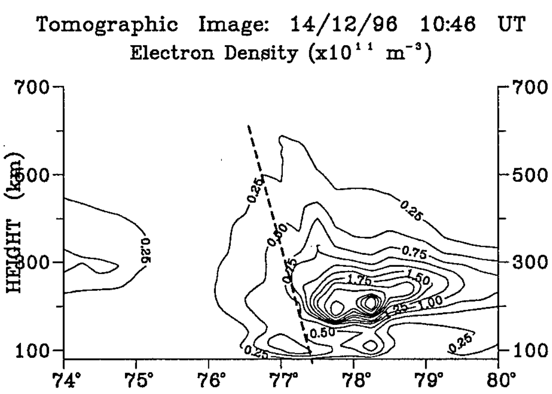


Figure 6. Tomographic image over Svalbard for the satellite pass crossing 78°N at 10:46 UT on 14 December 1996.

**Appendix G** Paper entitled 'Imaging and modelling of the main ionospheric trough using radio tomography' prepared for presentation at the IEE National Antennas and Propagation Meeting, to be held in York, UK in April 1999.

The paper, co-authored by J. A. T. Heaton, P. S. Cannon and N. C. Rogers of DERA, Malvern, describes in outline the radio tomographic imaging and modelling of the main trough using the experimental observations made at the NIMS receiving stations in UK.

# IMAGING AND MODELLING OF THE MAIN IONOSPHERIC TROUGH USING RADIO TOMOGRAPHY

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## INTRODUCTION

Radio tomography is a new experimental technique that produces images of the structuring of the electron concentration in the ionosphere. Phase-coherent radio signals are transmitted by the Navy Ionospheric Monitoring System (NIMS) satellites which are in polar orbits at altitudes of 1100 km. The transionospheric radio signals are monitored at a chain of ground-based receivers to infer the total electron content (TEC) along each ray path. The resultant data set is then inverted in a reconstruction algorithm to create a two-dimensional image of the distribution of electron concentration.

The main trough has been studied with a variety of different experimental techniques and instruments such as ionosondes, TEC and incoherent scatter. Previous case studies at high latitudes, with verification from European Incoherent Scatter (EISCAT) radar observations, have established tomographic imaging as a reliable technique for studying the trough (Kersley et al., 1). Although the experimental technique of ionospheric tomography is a recent addition to the observational tools, it has two distinct advantages. The first advantage is that it opens up the possibility of imaging spatial structure of the plasma over large latitudinal regions. From successive satellite passes it is possible to study the temporal variation of the location of the trough. The second advantage is that the low electron densities inherent in the trough region are difficult to observe using radar techniques, whereas tomographic images are not adversely affected by these regions of low electron concentration.

The current long-term deployment of receivers in UK is providing a wealth of information on the morphology and position of the main trough, a feature that is not well represented in existing ionospheric models used for propagation applications. The large database of tomographic images has been used to develop a new model for the trough over the European sector. In addition, tomographic images of the trough are being used to understand the propagation environment of the oblique sounders operated by the Defence Evaluation and Research Agency (DERA), Malvern.

## TOMOGRAPHIC IMAGING

In autumn 1997 a chain of five receiving systems was deployed in the UK, spanning more than 10 degrees latitude from Unst (60.8°N, 0.8°W) in the Shetlands Islands to Dartmouth (50.3°N, 3.6°W) on the south coast of England. The tomography experiment is designed for routine imaging of the ionosphere using the radio transmissions from the Navy Ionospheric Monitoring System (NIMS). They transmit phase-coherent radio signals at 150 and 400 MHz. The signals are used to make differential-doppler measurements, from which the relative total electron content is found along many ray paths as the satellite passes from horizon to horizon. The receivers run unattended and monitor all satellite passes above the horizon that are recorded for a duration of longer than two minutes. The receiver systems automatically record NIMS satellite passes and the data from the five sites are subsequently collated at the University of Wales, Aberystwyth. The chain of receiving stations provides a large number of TEC measurements from each satellite pass, allowing routine production of tomographic images of the mid-latitude ionosphere. The sites at Unst and Dartmouth are networked, allowing the phase data to be transferred to Aberystwyth via a phone line and modems.

Absolute TEC is estimated using a multi-station development of the least-squares calibration method described by Leitinger et al. (2). Compensation for the longitude difference between the satellite and the receiver is made using a cosine correction at the zenith angle of the ray path at 350-km altitude during nighttime and 280 km during the day.

The tomographic images have been reconstructed using the method described by Fremouw et al. (3), with an orthogonal basis set of functions formed from a range of Chapman profiles, with a linear gradient in the scale height of the topside ionosphere. This procedure is used to create an image of the large-scale features in the ionosphere, with subsequent processing by means of an Algebraic Reconstruction Technique (ART) algorithm to reconstruct the smaller-scale structures in the tomographic images. Ionosondes at Chilton (51.5°N,1.3°W) and Lerwick (60.2°N,1.2°W) make routine measurements of plasma frequency of the ionosphere at intervals of 30 minutes and these have been inverted using the POLAN procedure. Where

available, ionosonde measurements within 15 minutes of a satellite pass have been incorporated into the tomographic inversion to improve the reconstruction of the vertical profile of the bottomside ionosphere.

## RESULTS

The database of tomographic images indicates that the trough is routinely present over the UK at night and confirms its equatorward progression with increasing geomagnetic activity. Figure 2 shows a tomographic image from a satellite pass at 04:29 UT on 24 September 1998. The image reveals the main trough at around 55°N, under moderately disturbed geomagnetic conditions (Kp=5-). At a slightly earlier time on the following night the trough was located further south at around 50°N. The tomographic image at 04:01 UT, during these very disturbed conditions (Kp=8), is shown in Figure 3.

The tomographic image shown in Figure 4 has been reconstructed from a satellite pass at 22:40 UT on 10 February 1998. At a coincident time the DERA oblique sounder (Improved Radio Ionospheric Sounder, IRIS), deployed with a transmitter at Cove (52.3°N) and receivers at Malvern (52.1°N), Lossiemouth and Unst, was operating. The oblique incidence ionogram generated between Cove and Malvern is displayed in Figure 5. The crosses plotted onto the oblique ionogram represent a synthetic oblique ionogram that was generated by ray tracing through the tomographic image. It is evident that good agreement has been achieved between this simulated and recorded HF oblique propagation through the equatorward wall of the trough.

A procedure has been developed to create a model of the ionosphere over Europe to include the main trough. (Mitchell et al., 4). The model is derived from a real-time tomographic image over the UK that is extrapolated using three criteria. First the position of the trough minimum is mapped along the geomagnetic field that has been derived from the International Reference Geomagnetic Field (IGRF) model. A local-time dependence for the position of the trough minimum, using statistics derived from the database of tomographic images, is then applied. Finally, the absolute values of the electron densities in the extrapolated tomographic image are scaled according to gradients derived from the PIM model (Daniell et al., 5).

The tomographic image shown in Figure 6 has been reconstructed from a satellite pass at 02:59 UT on 23 November 1997. The minimum electron concentration in the trough can be seen at around 50°N. Using this modelling procedure it has been possible to generate a map of the electron concentration over Europe (Figure 7).

Comparisons between these models and isolated values of foF2 from ionosondes have been plotted in Figure 8. The comparisons indicate that the model provides a good representation of the electron concentration in the trough region.

## SUMMARY

Information derived from tomographic images has demonstrated the extreme variability of the ionosphere over the UK, with structures within the electron concentration usually associated with the auroral zone being found at UK latitudes under disturbed geomagnetic conditions. The tomographic images indicate that the main trough in F-layer electron concentration is routinely present over the northern UK at nighttime. With enhanced geomagnetic disturbance the progression of the trough to lower latitudes is evidenced, while extremely disturbed conditions result in the trough minimum being as far south as Northern France.

The applicability of the tomographic technique to the production of an ionospheric model, that includes the prominent main trough in the plasma electron concentration, has been demonstrated. Initial results indicate that the model shows potential for modelling an accurate representation of the main trough extending to some 30° in longitude from the location of the input data.

Ray tracing through the resulting tomographic images and the model of the mid-latitude trough has direct applications for the near-real-time determination of radio propagation conditions.

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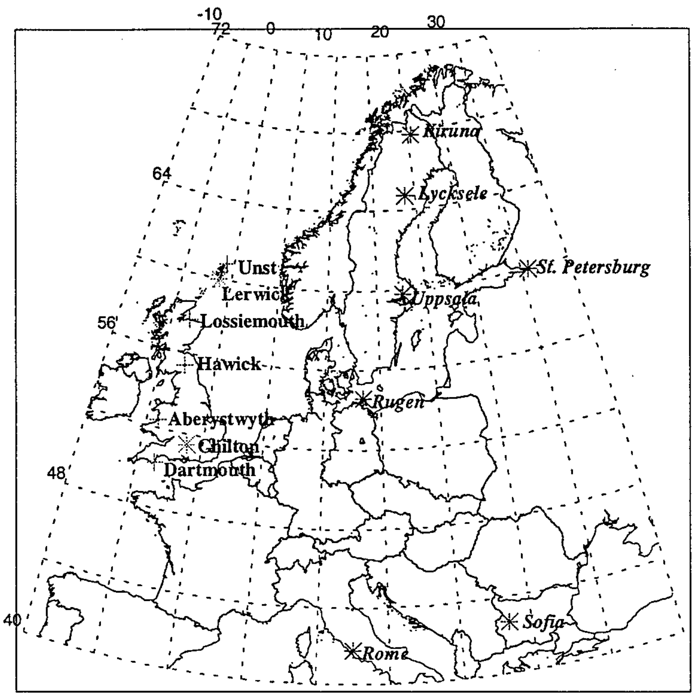


Figure 1. Map showing the locations of the tomography receivers (+) and ionosondes (*). The ionosondes used in the tomography are labelled with **plain bold text** and those used for independent comparison with the model are labelled with ***italics***.

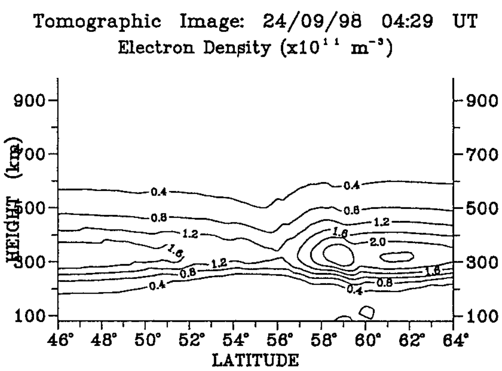


Figure 2. Tomographic image for the satellite pass crossing 55°N at 04:29 UT on 24 September 1998.

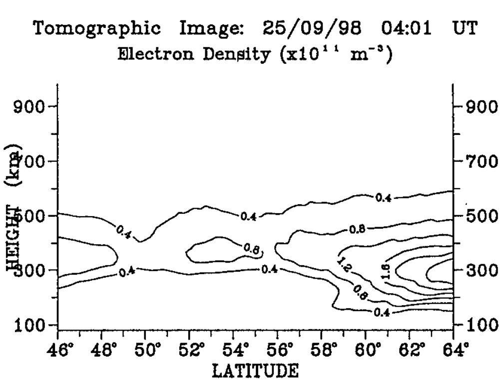


Figure 3. Tomographic image for the satellite pass crossing 55°N at 04:01 UT on 25 September 1998.

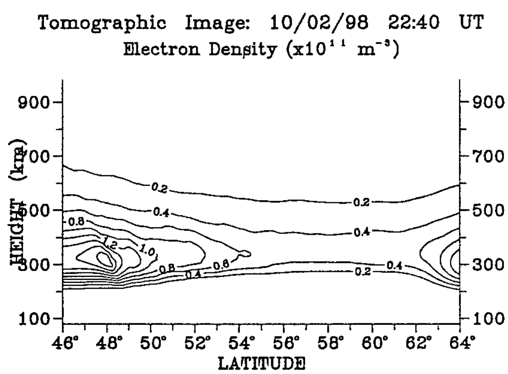


Figure 4. Tomographic image for the satellite pass crossing 55°N at 22:40 UT on 10 February 1998.

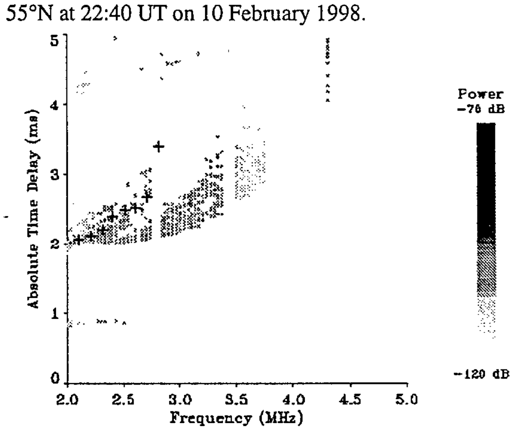


Figure 5. Oblique ionogram for the Cove-Malvern path at 22:41 UT on 10 February 1998. A synthetic ionogram obtained from the ray tracing through the tomographic image above is marked as crosses.

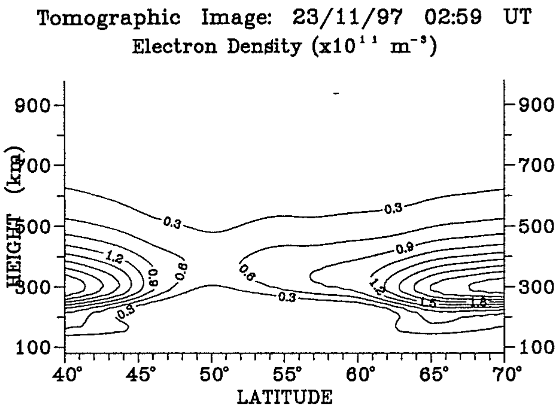


Figure 6. Tomographic image for the satellite pass crossing 55°N at 02:59 UT on 23 November 1997.

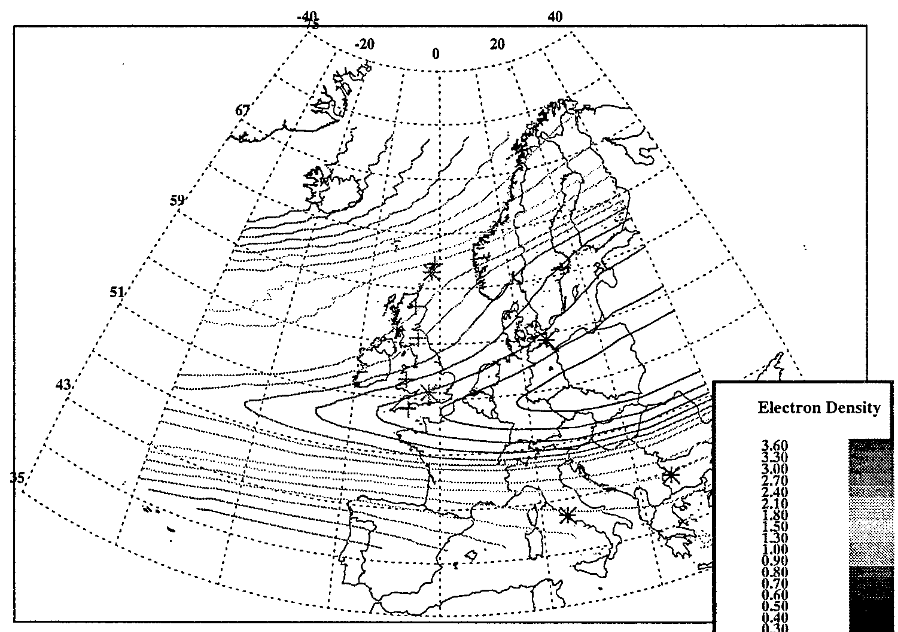


Figure 7. Model of NmF2 ($x10^{11}m^{-3}$) over Europe using the tomographic image from a satellite pass at 02:59 UT on 23 November 1997. The crosses show the locations of the tomography receivers in UK and the asterisks show the locations of ionosondes used in the tomography (light) and used for independent comparison (dark).

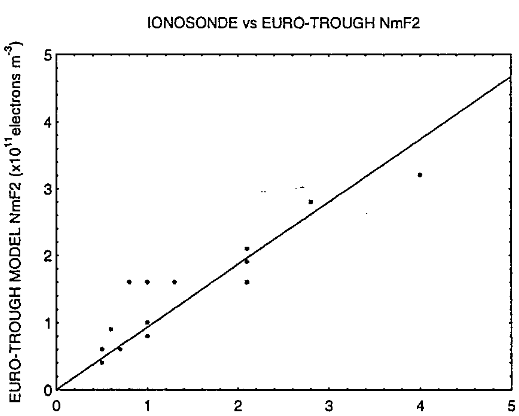


Figure 8. Comparison between the ionosondes and the trough model over Europe for six maps of NmF2.

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